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POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Méthodes d'analyse des usages et du potentiel des vélos-cargos en logistique urbaine

SUZANNE PIRIE

Département de mathématiques et de génie industriel

Thèse présentée en vue de l'obtention du diplôme de *Philosophiæ Doctor*

Génie industriel

Mai 2025

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POLYTECHNIQUE MONTRÉAL

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Cette thèse intitulée :

Méthodes d'analyse des usages et du potentiel des vélos-cargos en logistique urbaine

présentée par **Suzanne PIRIE**

en vue de l'obtention du diplôme de *Philosophiæ Doctor*

a été dûment acceptée par le jury d'examen constitué de :

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DÉDICACE

À Mme Durand, M. Thilloux, Mme Genet et Mme Direz,

Pour avoir su me donner l'envie d'apprendre.

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RÉSUMÉ

Les travaux de cette thèse portent sur les usages ainsi que le potentiel des vélos-cargos utilisés dans le cadre de la logistique urbaine à travers une analyse approfondie des conditions d'implémentation et des déterminants de leur efficacité. Dans un contexte de transition vers des modes de transport plus durables, la cyclologistique s'impose progressivement mais sûrement comme une alternative viable aux modes de transport motorisés traditionnels. Toutefois, l'implémentation et le déploiement de cette solution demeurent des défis, notamment en raison des contraintes liées à la variabilité des contextes géographiques, démographiques et politiques des milieux urbains, à la performance économique, environnementale et sociétale de ce mode de livraison.

Les travaux de cette thèse sont étayés par quatre articles qui traitent de : l'évaluation empirique de la viabilité des vélos-cargos, l'analyse des pratiques de livraison et des défis opérationnels, l'exploration du potentiel de la cyclologistique dans les villes de taille moyenne et l'examen des solutions de micromobilité complémentaires pour la logistique des ménages. Chaque article repose sur différentes méthodes quantitatives et qualitatives, pour lesquelles le vélo-cargo est à la fois outil et sujet d'analyse.

Le premier article s'appuie sur l'expérience de l'initiative "Livraison Arc-en-Ciel" lancée à Montréal durant la pandémie de Covid-19. Cette étude met en évidence les facteurs clés influençant le succès de la livraison à vélo-cargo, notamment la densité urbaine, les caractéristiques sociodémographiques des clients et les stratégies de communication mises en place. Le deuxième article porte sur l'analyse des pratiques de livraison avec des vélos-cargos et des contraintes liées à ce nouveau véhicule. Cette étude révèle que l'organisation des tournées de livraison est impactée fortement par la qualité des infrastructures cyclables, des conditions météorologiques et de l'offre de stationnement pour ce type de véhicule. Par ailleurs, les préférences des livreurs lors des livraisons et leurs perceptions des risques influencent directement leur comportement sur la route. Le troisième article représente un changement de perspective, son objectif étant de sortir du prisme des grandes villes. Cet article explore donc la pertinence des vélos-cargos dans des contextes urbains moins denses et se base sur des profils des villes fortement diversifié. Une approche multicritère permet d'évaluer les conditions favorables à leur déploiement, en intégrant des variables telles que la densité urbaine, l'accessibilité des infrastructures et les conditions météorologiques spécifiques à l'espace géographique étudié. Cette étude met en lumière les

différences entre les grandes métropoles et les villes moyennes en matière de logistique urbaine en proposant des actions ciblées par groupement de villes. Enfin, le quatrième article s'intéresse à une solution de micromobilité complémentaire qu'est le partage de remorques à vélo par une initiative citoyenne. Cette initiative s'inscrit dans le cadre spécifique de la logistique des ménages. Cette analyse démontre que l'adoption de telles solutions varie en fonction des configurations urbaines et des profils des ménages.

En conclusion, les travaux proposés dans cette thèse mettent en évidence le potentiel des vélos-cargos comme solution durable et viable pour la logistique urbaine, tout en soulignant les défis liés à leur adoption à moyenne et grande échelle. Les résultats obtenus offrent des perspectives intéressantes pour les décideurs publics et les acteurs du secteur de la logistique urbaine, en les guidant vers des stratégies de déploiement et d'intégration adaptées à ce mode de livraison spécifiquement. De futurs projets de recherche pourront approfondir l'impact des évolutions technologiques et des politiques publiques sur le développement de la cyclologistique. /

ABSTRACT

This thesis looks at the uses and potential of cargo bikes for urban logistics, through an in-depth analysis of the conditions under which they are implemented and the factors that determine their effectiveness. In a context of transition towards more sustainable modes of transport, cycle logistics is gradually but surely establishing itself as a viable alternative to traditional motorised modes of transport. However, the implementation and deployment of this solution remain a challenge, in particular because of the constraints linked to the variability of the geographical, demographic and political contexts of urban environments, and to the economic, environmental and societal performance of this mode of delivery.

The work in this thesis is supported by four articles that deal with: an empirical assessment of the viability of cargo bikes, an analysis of delivery practices and operational challenges, an exploration of the potential of cyclologistics in medium-sized cities, and an examination of complementary micromobility solutions for household logistics. Each article is based on different quantitative and qualitative methods, for which the cargo bike is both tool and subject of analysis.

The first article is based on the experience of the “Livraison Arc-en-Ciel” initiative launched in Montreal during the Covid-19 pandemic. The study highlights the key factors influencing the success of cargo bike delivery, including urban density, the socio-demographic characteristics of customers and the communication strategies put in place. The second article analyses delivery practices using cargo bikes and the constraints associated with this new vehicle. This study reveals that the organisation of delivery rounds is strongly impacted by the quality of cycling infrastructure, weather conditions and the availability of parking for this type of vehicle. In addition, delivery drivers' preferences when making deliveries and their perceptions of the risks directly influence their behaviour on the road. The third article represents a change of perspective, the aim being to move away from the prism of large cities. This article therefore explores the relevance of cycle-cargoes in less dense urban contexts and is based on highly diverse city profiles. A multi-criteria approach is used to assess the conditions favourable to their deployment, incorporating variables such as urban density, infrastructure accessibility and weather conditions specific to the geographical area under study. This study highlights the differences between major metropolises and medium-sized towns in terms of urban logistics, proposing targeted actions for groups of towns. Finally, the fourth article looks at a complementary micromobility solution: the sharing of

bicycle trailers by a citizens' initiative. This initiative falls within the specific framework of household logistics. This analysis shows that the adoption of such solutions varies according to urban configurations and household profiles.

In conclusion, the work proposed in this thesis highlights the potential of cargo bikes as a sustainable and viable solution for urban logistics, while highlighting the challenges associated with their adoption on a medium and large scale. The results obtained offer interesting prospects for public decision-makers and players in the urban logistics sector, guiding them towards deployment and integration strategies specifically adapted to this mode of delivery. Future research projects could examine the impact of technological developments and public policies on the development of cyclelogistics.

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LISTE DES SIGLES ET ABRÉVIATIONS

AHD	*Attended Home Delivery problem*
AHP	*Analytic hierarchy process*
AIC	*Akaike information criterion*
ARI	*Adjusted rand index*
BCLF	*Belgian cyclologistics federation*
BIC	*Bayesian information criterion*
CCU	Centre de consolidation urbain
CÉR	Comité d'éthique en recherche
CNESST	Commission des normes, de l'équité, de la santé et de la sécurité du travail
CUBF	Codes d'utilisation des biens-fonds
DIY	*Do it yourself*
FSA	*Forward sortation area*
GES	Gaz à Effet de Serre
GHG	*Greenhouse gaz emissions*
CCCB	*City changer cargo bike*
GPS	*Global positionning system*
HAC	*Hierarchical ascending classification*
ICC	*Intra Class Correlation*
IFT	*International Forum on Transportation*
MCDA	*Multi-criteria decision analysis*
NOx	Oxyde d'azote
NREL	*National renewable energy laboratory*
OHS	*Occupational health and safety*
OSM	*Open Street Map*
PAM	*Partition around medoids*
PIB	Produit intérieur brut

PM	Particules fines
PPE	*Personal protection equipment*
SCLP	*Single container loading problem*
SDC	Société de développement commercial
SML	*Swiss messenger logistics*
UN	*United Nations*
WSMD	*Work-related musculoskeletal disorder*
ZFE	Zone à Faible Émission

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CHAPITRE 1 INTRODUCTION

1.1 Contexte

La transition vers des modes de transport plus durables est devenue une priorité dans plusieurs régions du monde, notamment en réponse aux défis environnementaux et urbains croissants. Le secteur du transport de marchandises, en particulier, joue un rôle clé dans l'atteinte des objectifs de réduction des émissions de gaz à effet de serre (GES). Toutefois, malgré son importance, il reste souvent sous-documenté, rendant complexe l'évaluation précise de son impact et des mesures nécessaires à sa transformation. De plus, la demande en livraisons urbaines demeure croissante. On estime qu'à Montréal, 900 000 livraisons sont effectuées quotidiennement (Meloche et al., 2025). Dans ce contexte, la cyclologistique apparaît comme une solution innovante et en pleine expansion. Plusieurs initiatives émergent à travers le Canada, le Québec et d'autres régions de la francophonie pour favoriser l'intégration des vélos-cargos dans la logistique urbaine. Que ce soit à travers des projets pilotes, des programmes de soutien ou des incitatifs financiers, les gouvernements et les acteurs du transport cherchent à structurer cette nouvelle pratique du dernier kilomètre. Cette section propose un tour d'horizon du transport de marchandises et de la cyclologistique, en mettant en lumière les tendances et initiatives mises en place au Canada, au Québec et dans différents pays de la francophonie.

1.1.1 Le transport de marchandises à l'échelle du Canada et du Québec

En 2023, le secteur du transport et de l'entreposage représentait 4 % du produit intérieur brut (PIB) canadien (T. Canada, 2023). Par ailleurs, en 2021, le transport routier de marchandises a généré 26,51 mégatonnes d'émissions de CO_2 équivalent (T. Canada, 2023). Au Québec, le secteur des transports constitue la principale source d'émissions de gaz à effet de serre (GES), représentant 43 % du total provincial (Gouvernement du Québec, 2024). Toutefois, qu'il s'agisse du Canada ou du Québec, les données spécifiques au transport de marchandises, qu'il soit interurbain ou du dernier kilomètre, demeurent limitées, ce qui rend complexe l'établissement d'un portrait précis de la situation.

À Montréal, plusieurs stratégies ont été mises en place pour favoriser la décarbonation du transport urbain de marchandises. Le Plan climat 2020-2030 (Montréal, 2020) prévoit notamment l'électrification des véhicules de livraison et le déploiement de projets pilotes en logistique urbaine.

Cette orientation est réaffirmée dans la Stratégie d'électrification des transports (Montréal, 2021b), qui introduit également l'expérimentation d'une zone à faibles émissions (ZFE). Toutefois, le Plan stratégique Montréal 2030 (Montréal, 2021a) se concentre principalement sur la mobilité des passagers et ne propose pas de mesures spécifiques en matière de logistique urbaine. De même, la Feuille de route vers des transports décarbonés (Montréal, 2023) évoque brièvement le transfert modal des marchandises vers des modes de transport à faibles émissions, sans pour autant détailler les moyens concrets ni d'objectifs chiffrés associés. Il faudra attendre la publication du projet de Plan d'urbanisme et de mobilité 2050 (Montréal, 2024) ainsi que du Plan d'action pour la logistique urbaine (en cours de production par la Ville de Montréal) pour voir ces enjeux abordés de manière plus approfondie. On y retrouve notamment l'affectation des sols pour établir des mini-entrepôts urbains, la mise en place de zones à faibles émissions et la généralisation des initiatives de cyclologistique à l'échelle de la ville.

Depuis 2019, Montréal s'implique activement dans le développement de la cyclologistique, une approche visant à réduire les émissions du secteur des transports tout en améliorant la sécurité routière, en cohérence avec sa politique de « Vision Zéro » (Montréal, 2019). La cyclologistique désigne l'ensemble des activités commerciales de transport de marchandises réalisées exclusivement à l'aide de cycles, pouvant être à deux ou trois roues, avec ou sans assistance électrique, à l'exclusion des cyclomoteurs, scooters ou motos électriques. Elle inclut notamment l'usage de vélos cargos ou triporteurs, dont la conception permet le transport de charges importantes, tout en maintenant une vitesse modérée et une empreinte environnementale faible.

1.1.2 L'écosystème de la cyclologistique dans la francophonie

Il serait impossible de recenser de manière objective et exhaustive l'ensemble des programmes, initiatives et fédérations qui portent et œuvrent sur l'utilisation des vélos-cargos comme mode de transport pour les marchandises. Cependant, à l'échelle des principaux acteurs la francophonie, une telle recension illustre le dynamisme et l'organisation de l'industrie de la livraison avec des vélos-cargos. Ce choix de se concentrer sur la francophonie s'explique par l'existence de relations durables entre ces pays, ainsi que par l'influence notable qu'exercent certaines initiatives francophones et notamment européennes sur le développement des politiques et pratiques cyclologistiques au Québec.

- En France

Depuis 2019 se déploie en France l' « Association Nationale des Boîtes à Vélo – France, l'union des professionnel.les à vélo » (« Boîtes à vélo ») qui regroupe quatorze autres entités régionales. Outre leur mission de représentation, l'association offre un programme nommé cyclo-cargologie. Ce programme, spécifiquement destiné aux activités de livraison du dernier kilomètre, vise à sensibiliser et accompagner la transition vers le vélo-cargo. Le programme forme aussi aux différents métiers liés à la livraison du dernier kilomètre et offre des outils d'interconnexion pour aider à la mutualisation des flux avec des vélos-cargos. Le programme Colis'Activ (« Le programme ColisActiv' ») permet de subventionner les livraisons à vélo pour inciter les donneurs d'ordre à transitionner vers des modes de livraison actifs. Il existe aussi la fédération professionnelle de cyclologistique (« Fédération professionnelle de cyclologistique »), dont l'objectif est de promouvoir la filière française de cyclologistique et d'avoir une voix commune pour tous les acteurs auprès des pouvoirs publics ainsi que des partenaires. La fédération a pour mission de concevoir, rédiger et diffuser des guides sur des enjeux propres à la cyclologistique. De plus, jusqu'en février 2025, l'état Français avait un programme d'aide à l'achat d'un vélo-cargo. Cette aide allait de 2000 euros pour un particulier à 1000 euros pour une entreprise.

- En Belgique

En Belgique, la fédération belge de cyclologistique (*BCLF - Belgian Cycle Logistics Federation - BCLF*, 2024) forme un réseau d'opérateurs et de partenaires qui partagent une vision commune et offrent de nouvelles perspectives à la cylologistique. La BCLF œuvre pour obtenir les conditions favorables à l'accélération du développement de la cyclologistique. Les membres, partenaires et citoyens ont la possibilité de signer la déclaration pour la cyclologistique. Le programme « Cairgo bike » (*Cairgo Bike, c'est quoi? | Cairgobike*), cofinancé par Bruxelles Mobilité et le fonds européen de développement régional, permet aux citoyens et entreprises de tester et adopter des différents types de vélos-cargos. L'initiative regroupe aussi différentes parties prenantes pour accompagner les projets et mesurer les retombées.

- En Suisse

En Suisse, le programme City Changer Cargo Bike (CCCB) (*Des initiatives pour développer l'usage des vélos-cargos*), soutenu par le programme Horizon 2020 de l'Union Européenne a pour objectif de promouvoir l'utilisation du vélo-cargo pour les citoyens et les entreprises. L'association

patronale pour les services de coursiers urbains (*SML - SWISSMESSENGERLOGISTIC*) a comme mission de développer une convention collective de travail pour les messagers à vélos.

- Au Luxembourg

Pour le Luxembourg, le seul programme trouvé dans le cadre de cette recherche d'initiatives pour développer la cyclologistique est le programme « Klimabonus Mobilitéit » qui permet d'obtenir de l'aide financière à l'achat d'un vélo-cargo. Le programme a échu en 2024.

- Au Canada (hors Québec)

Pour ce qui est du reste du Canada, à l'exception du Québec (couvert à la section 1.1.3), il existe différentes initiatives de cyclologistique. L'institut Pembina a un centre de données urbaines, financé en partie par la banque royale du Canada (RBC) (*Urban Freight Data Hub | Pembina Institute*). Ce centre de données urbaines permet aux décideurs publics de faire des politiques publiques appropriées selon les données de chaque ville. La ville de Vancouver a effectué un projet pilote en 2021 pour accélérer la transition vers des vélos-cargos pour la livraison du dernier kilomètre (Vancouver).

En conclusion, il existe de nombreuses initiatives qui portent sur la cyclologistique. La cyclologistique connaît un essor significatif dans plusieurs pays, avec des initiatives variées adaptées aux contextes nationaux et/ou régionaux. Ces initiatives témoignent d'une volonté croissante d'intégrer le vélo-cargo dans les chaînes logistiques, en réponse aux enjeux environnementaux et urbains contemporains.

1.1.3 La cyclologistique dans le contexte du Québec

Au Québec, plusieurs entreprises se partagent le marché de la cyclologistique. Parmi les transporteurs, certains disposent d'une flotte mixte composée de vans, de véhicules électriques légers et de vélos-cargos (désignés comme « joueurs mixtes »), tandis que d'autres opèrent exclusivement avec des vélos-cargos (appelés « joueurs purs »).

En 2019, le projet Colibri voit le jour dans l'ancienne gare d'autocars de Montréal. Il s'agit d'un espace partagé entre différentes entreprises utilisant des vélos-cargos. Les résultats de ce projet pilote démontrent que ces véhicules sont 15 % plus efficaces que les camions dans les zones de livraison (Jalon Montréal, 2020). Lors de la pandémie de Covid-19, l'initiative « Livraison Arc-en-Ciel » a permis d'offrir une solution de livraison à faible coût aux commerçants touchés par les

fermetures successives imposées par le gouvernement (Figure 1.1). Au cours de cette période, plus de 6 500 livraisons ont été effectuées en environ 16 semaines. Depuis, un second micro-hub a vu le jour en 2022 sous le nom de Colibri Iberville. Ce dernier continue de démontrer l'efficacité de la cyclologistique pour la livraison urbaine et est géré par la Coop Carbone (www.coopcarbone.coop). À Québec, un projet pilote de livraison à vélo-cargo est lancé à l'été 2024, avec un micro-hub situé dans le Vieux-Québec. Ce projet rassemble trois transporteurs : Nationex, Purolator et Mon quartier en boîte. L'organisation Envoi Québec centralise les différentes options d'envoi pour les commerçants de la région, à l'image de son pendant montréalais, Envoi Montréal.

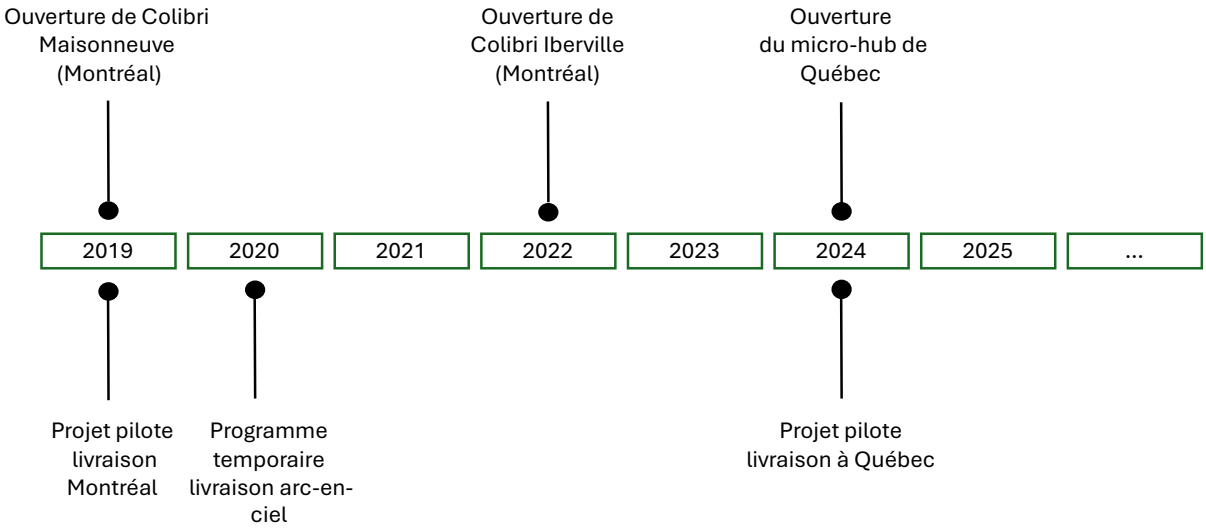


Figure 1.1 Synthèse des initiatives de cyclologistique au Québec

Au Québec, il est possible de distinguer deux grandes catégories de joueurs au sein de l'écosystème de la cyclologistique, soit les joueurs purs qui opèrent uniquement avec des vélos-cargos et les joueurs mixtes, qui opèrent traditionnellement des camions et des vans mais qui ont ajouté une flotte de vélos-cargos à leurs opérations. Au moment d'écrire cette thèse, les joueurs mixtes sont des entreprises nationales ou internationales, intéressées à gagner et/ou maintenir des parts de marché et diversifier leurs opérations afin de faire face à des défis spécifiques comme la congestion dans les milieux denses et urbains. En opposition mais avec une certaine complémentarité, les joueurs purs sont des petites entreprises (souvent auto-entrepreneurs ou travailleurs autonomes) qui se spécialisent dans les petits flux, pour des commerces ayant des besoins spécifiques qui ne

peuvent pas avoir de transbordement (denrées périssables, petits colis, partenariats entre commerces etc.).

L'effet de la pandémie de Covid-19 n'est pas à sous-estimer dans l'établissement de la cyclologistique à Montréal. Grâce à l'initiative et au regroupement de plusieurs entreprises qui opèrent à vélo-cargo à Montréal lors de la première phase de la pandémie, la livraison par vélos-cargos a gagné en popularité en en raison d'être et de subsister à Montréal, notamment auprès de petits commerces qui ont pu vivre une logistique alternative et fiable pendant quelques mois.

Étant donné qu'il n'existe encore aucune politique locale au Québec, telles des zones faibles émissions ou des régulations spécifiques

1.2 Problématique

Au Canada et au Québec, le secteur des transports constitue l'une des principales sources d'émissions de CO_2, et les initiatives visant à réduire son empreinte environnementale se multiplient (électrification massive des transports, cyclologistique, réflexion sur la mise en place des zones basses émissions etc.). Parmi celles-ci, la cyclologistique, qui englobe les activités de livraison effectuées à l'aide de vélos-cargos, s'impose progressivement comme une alternative crédible aux modes motorisés traditionnels. Si plusieurs grandes villes, dont Montréal, ont lancé des projets pilotes et encouragé l'expansion de la cyclologistique, la mise à l'échelle de ces solutions demeure un défi. L'adoption et le déploiement des vélos-cargos en logistique urbaine est encore freiné par plusieurs facteurs : infrastructures inadaptées, conditions météorologiques complexes pour le Québec, manque de prise en compte des préférences des livreurs et variabilité des contextes urbains entre métropoles et villes moyennes.

Dans ce contexte, il devient essentiel d'analyser en profondeur les usages et le potentiel des vélos-cargos comme mode de livraison. Cette recherche s'inscrit ainsi dans une démarche d'exploration des conditions nécessaires à leur adoption et des variables influençant leur efficacité. L'objectif est de comprendre comment ces véhicules peuvent s'intégrer durablement dans les systèmes logistiques urbains, en tenant compte à la fois des caractéristiques des livraisons effectuées, des caractéristiques inhérentes au véhicule même ainsi que des spécificités des environnements urbains dans lesquels les livraisons ont lieu.

1.3 Objectifs

De la problématique présentée à la section 1.2 découlent certains objectifs. Ceux-ci sont présentés avec les articles qui ont vocation à y répondre.

- Démontrer la viabilité du vélo-cargo comme mode de livraison à part entière.

L'initiative spontanée de livraison à vélo-cargo mise en place à Montréal durant la pandémie de Covid-19 permet d'évaluer empiriquement son efficacité dans un contexte de forte demande. Une analyse quantitative des livraisons réalisées met en évidence des facteurs influençant le succès de cette solution, notamment la densité urbaine, les caractéristiques sociodémographiques des clients et la présence de stratégies de communication adaptées (article 1). Cette étude constitue une preuve de concept démontrant que les vélos-cargos peuvent s'intégrer efficacement dans la logistique urbaine du dernier kilomètre.

- Analyser les pratiques ainsi que les défis opérationnels et liés aux infrastructures dans l'utilisation des vélos-cargos en logistique urbaine.

Les performances des livraisons à vélo-cargo sont analysées en fonction des infrastructures cyclables, des conditions météorologiques et de l'organisation des tournées de livraison (article 2). Cet article montre que l'absence d'aménagements dédiés, la variabilité des conditions climatiques et les préférences des livreurs influencent directement l'adoption et l'efficacité de ces véhicules. Ces résultats soulignent la nécessité d'adaptations infrastructurelles et réglementaires pour favoriser une intégration durable des vélos-cargos dans les systèmes logistiques urbains.

- Évaluer le potentiel d'implémentation d'un système de livraison avec des vélos-cargos en sortant du prisme des métropoles.

Une évaluation du potentiel des vélos-cargos dans les villes de taille moyenne est réalisée à l'aide d'une approche multicritère intégrant la densité urbaine, les infrastructures cyclables et les flux commerciaux (article 3). L'étude identifie les conditions favorables au déploiement d'initiatives de livraisons avec des vélos-cargos et permet de distinguer les contextes où la cyclologistique peut être un levier efficace pour une logistique urbaine durable. Ces résultats offrent une première base méthodologique pour la mise en œuvre de systèmes de livraison par vélos-cargos en dehors des grandes agglomérations.

- Explorer les solutions complémentaires de micromobilité, analogue aux vélos-cargos, dans le cadre de la logistique urbaine des ménages.

L'analyse des services de remorques à vélo partagées a permis d'évaluer leur rôle en tant qu'alternative aux véhicules motorisés pour les besoins logistiques des ménages (article 4). L'étude révèle que leur adoption dépend fortement de la configuration urbaine et des usages spécifiques des citoyens, notamment pour le transport de denrées alimentaires ou de matériel volumineux. Ces résultats contribuent à élargir la réflexion sur l'intégration de solutions de micromobilité au sein des politiques et pratiques de transport durable.

Le lien entre les différents objectifs et les articles sont illustrés à la Figure 1.2.

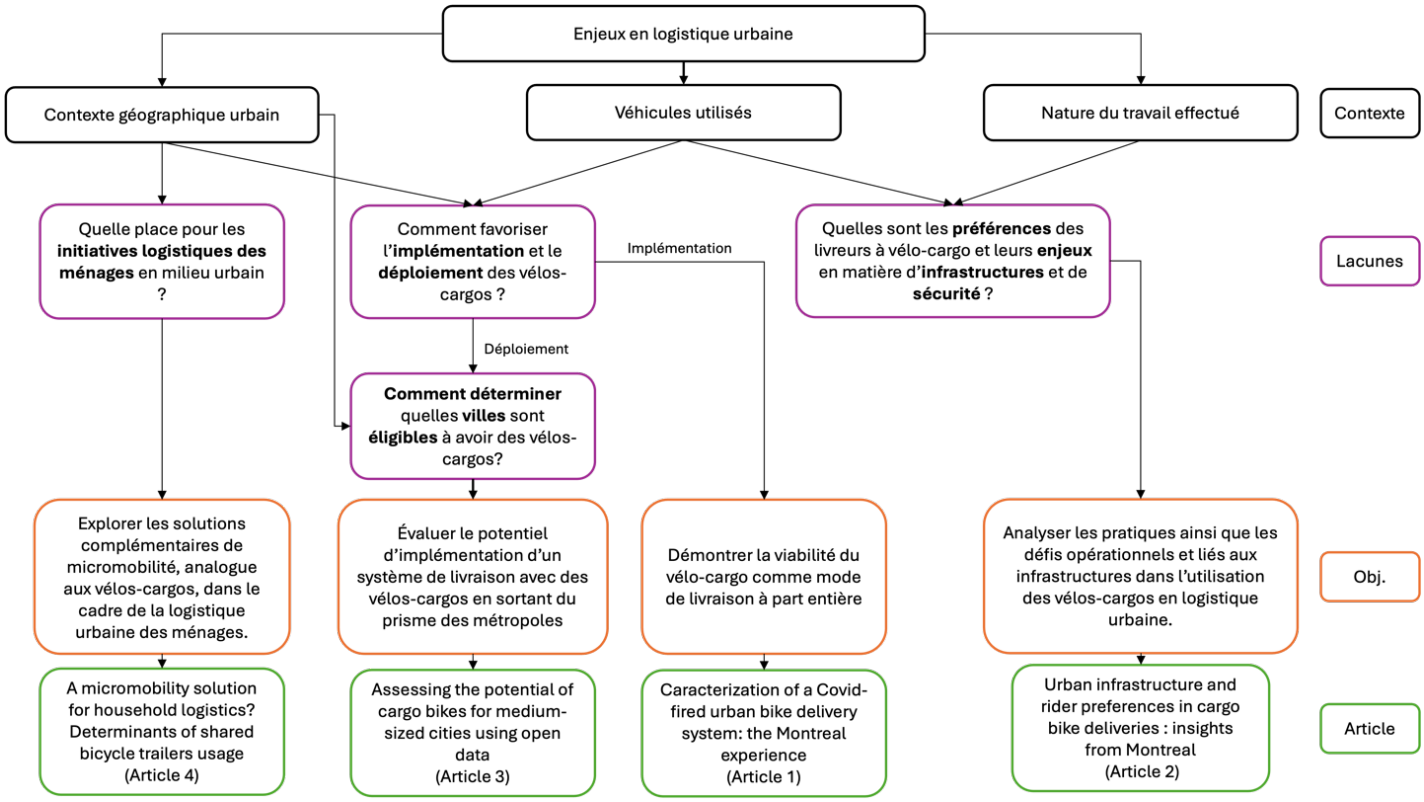


Figure 1.2 Synthèse des liens entre objectifs, lacunes identifiées et articles

1.4 Structure du document

Cette thèse est divisée en plusieurs chapitres. Après cette introduction (Chapitre 1) se trouve la revue de littérature (Chapitre 2) qui détaille les enjeux en logistique urbaine et les différentes lacunes identifiées dans le cadre de ces travaux de thèse. Le Chapitre 3 est une présentation de la trame narrative ainsi que des démarches méthodologiques effectuées pour les différents articles.

Une présentation à haut niveau des données utilisées est aussi présente au Chapitre 3. Les chapitres 4 à 7 inclus sont les manuscrits des différents articles de cette thèse. Finalement, le Chapitre 8 est la discussion générale à partir des principaux résultats et le Chapitre 9 regroupe la conclusion générale de cette thèse, les limites ainsi que les perspectives qui en découlent.

1.5 Utilisation de l'intelligence artificielle

Dans le cadre de cette thèse, l'intelligence artificielle a été utilisée comme un outil d'assistance à plusieurs niveaux. Tout d'abord, elle a facilité l'amélioration syntaxique et orthographique du texte. Par ailleurs, elle a contribué à assurer la cohérence de l'enchaînement de certains paragraphes et a servi d'outil de traduction pour certains termes ou passages du texte. Ensuite, dans l'élaboration et l'optimisation du code avec Python et R, l'intelligence artificielle a permis d'apporter des modifications rapides, d'ajouter des fonctionnalités et d'effectuer des tests, notamment pour la génération de graphiques.

Toutefois, son utilisation a été limitée aux tâches précédemment mentionnées. À aucun moment, les outils d'intelligence artificielle n'ont été employés pour générer de nouvelles idées destinées aux articles de la thèse, ni pour traiter des données privées de compagnies, garantissant ainsi le respect des principes éthiques et de confidentialité. De même, aucune génération d'images n'a été effectuée via ces outils. Parmi les solutions d'intelligence artificielle utilisées figurent *ChatGPT* pour l'assistance rédactionnelle et la vérification de la cohérence textuelle ainsi que pour l'aide à la rédaction de code. *DeepL Write* et *DeepL Traduction* ont été utilisés pour l'amélioration linguistique et la traduction, notamment pour la rédaction des articles en anglais.

CHAPITRE 2 REVUE DE LITTÉRATURE

La logistique urbaine connaît une transformation majeure sous l'effet conjugué de l'essor du commerce en ligne, des pressions environnementales et de la nécessité d'adapter les infrastructures aux nouvelles formes de mobilité. Cette évolution soulève des défis complexes, qui touchent aussi bien l'organisation des flux de marchandises, l'intégration des véhicules utilisés que les conditions de travail des livreurs. Dans ce contexte, les vélos-cargos émergent comme une solution prometteuse pour réduire l'empreinte carbone du dernier kilomètre et limiter les nuisances associées à la congestion urbaine. Cependant, leur adoption à grande échelle demeure conditionnée par de multiples facteurs, allant de la mise en place d'infrastructures adaptées à la viabilité économique des modèles logistiques qui les intégrent.

Cette revue de littérature présente et analyse ces enjeux à travers trois axes principaux. La première partie de cette revue de littérature dresse un aperçu des principaux enjeux de la logistique urbaine, constituant ainsi le cadre de référence dans lequel s'inscrivent les travaux de cette thèse. Ces enjeux permettent d'identifier des questions clés pour lesquelles des lacunes subsistent, orientant ainsi l'analyse vers les pans de la littérature pertinents. Chaque lacune mise en évidence dans cette revue conduit à la rédaction d'un article (publié ou soumis), qui sera présenté dans les chapitres suivants (Figure 2.1.)

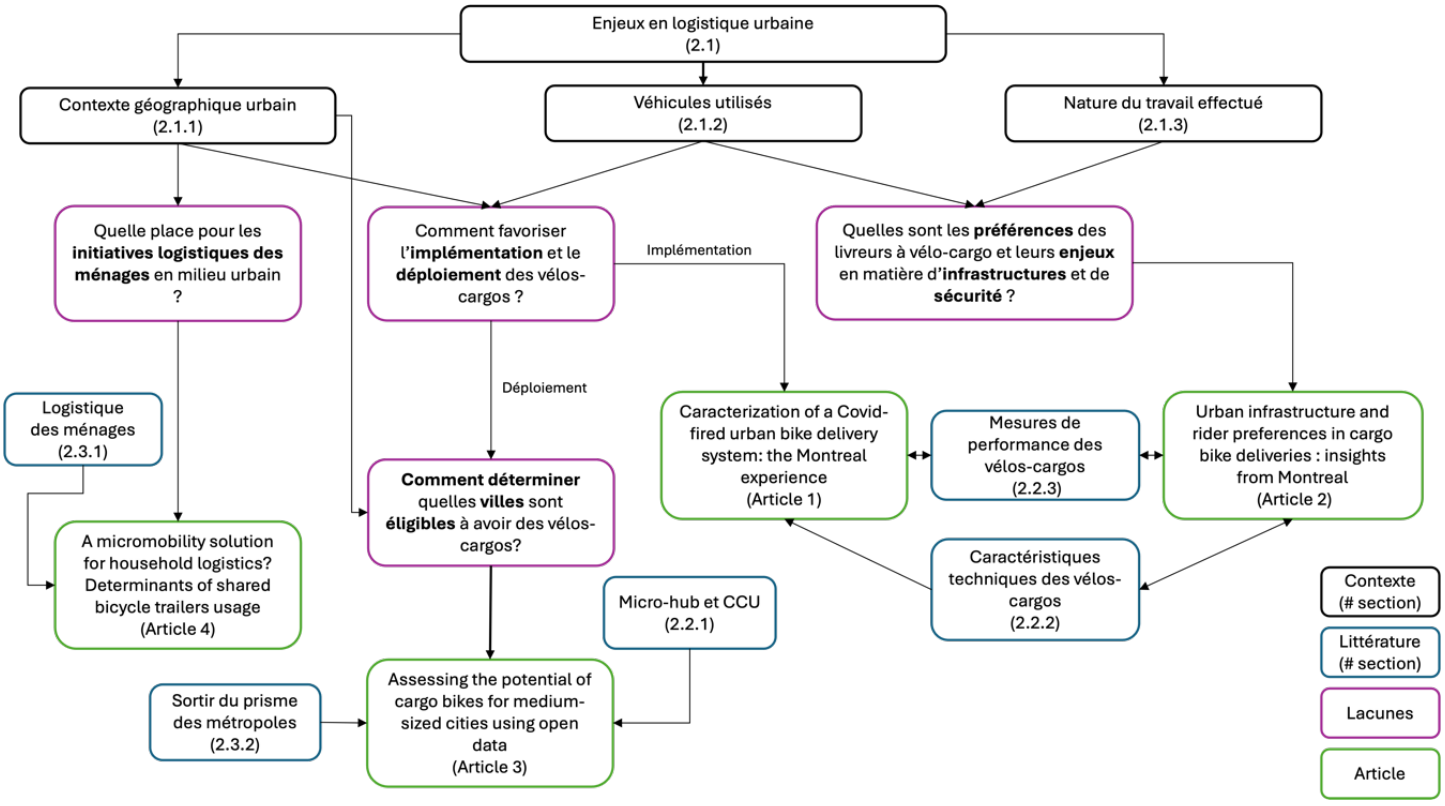


Figure 2.1 Plan de la revue de littérature

2.1 Enjeux en logistique urbaine

La logistique urbaine est confrontée à plusieurs enjeux interdépendants, qui influencent directement l'efficacité, la durabilité et la sécurité des activités de livraison ainsi que des humains qui les effectuent. Ces défis peuvent être regroupés en trois grandes catégories : les contraintes liées au contexte géographique urbain, les spécificités des véhicules utilisés et les conditions de travail des acteurs impliqués dans ces opérations. D'une part, les conflits d'usage de la voirie et la gestion de la bordure de rue accentuent les tensions entre les différents modes de transport, complexifiant l'intégration de solution de logistique durable. D'autre part, la transition vers des véhicules à faibles émissions, comme les vélos-cargos, représente une opportunité sous-exploitée pour atténuer les externalités environnementales du transport de marchandises. Enfin, les conditions de travail des livreurs, notamment ceux opérant à vélo, demeurent un angle mort de la recherche scientifique, alors même que leur sécurité et leur bien-être influencent la viabilité et la

pérennité de ces nouvelles pratiques logistiques. Cette section vise ainsi à analyser ces enjeux et à identifier les leviers d'action pour une logistique urbaine plus efficiente et durable.

2.1.1 Les enjeux liés au contexte géographique urbain

Les activités de livraison en milieu urbain entraînent des enjeux vis-à-vis de la sécurité d'un grand nombre d'usagers de la route, dont particulièrement les usagers les plus vulnérables (piétons adultes comme enfants, cyclistes, personnes en situation de handicap etc.). Au Québec, le rapport partiel de la SAAQ fait état de 1 223 cyclistes accidentés (dont 58 blessés graves et 12 décès) soit une augmentation de 5,1 % par rapport à l'année 2023 ainsi que de 1604 piétons accidentés (dont 136 blessés graves, 42 décès) pour une augmentation de 3,0 % par rapport à 2023 (SAAQ, 2024). Aux États-Unis, McDonald et al. (2019) démontrent une augmentation de la tendance de la fatalité de 17 % entre 2005 et 2015 pour les accidents attribuables à la livraison de marchandises en ville. Ces résultats ne sont pas attribuables qu'aux États-Unis. En effet, Pokorny et al. (2017) établissent que les accidents entre poids lourds et cyclistes se déroulent à 77 % en ville et ont lieu le matin ou l'après-midi et dans des conditions où la visibilité était correcte. Les deux articles précédemment mentionnés identifient notamment comme facteurs de risques la réduction des fenêtres temporelles de livraisons, qui entraine une augmentation de la vitesse des véhicules, la sous-traitance des activités de livraisons dans le cadre de l'économie à la tâche (« *gig economy* ») ainsi que les conflits d'usage de la route.

Les conflits d'usages de la route peuvent être causés par la demande accrue d'accès aux espaces en bords de rue pour différentes activités (circulation apaisée avec la présence de pistes cyclables, retrait des ordures ménagères, livraisons de marchandises à domicile etc.). En général, les possibilités de stationnement pour les véhicules de livraison sont limitées, en particulier dans les zones urbaines denses, et entraînent des comportements indésirables, tels que les files d'attente, le stationnement en double file et/ou dangereux (Conway et al., 2017a; Gonzalez-Calderon et al., 2022) (Figure 2.2), mais aussi un nombre accru d'amendes pour certains véhicules (Holguín-Veras et al., 2011). Pour le cas spécifique de l'utilisation des vélos-cargos pour la livraison de marchandises, l'étude menée par Dalla Chiara et al. (2023) permet d'obtenir un portrait partiel des stratégies de stationnement en bord de rue effectuées par les livreurs à vélos-cargos. Dans leur étude, située à Seattle (États-Unis), les auteurs identifient que 79,9 % du temps, les livreurs à vélos-

cargos choisissent de se stationner sur le trottoir, puis sur en bord de rue (< 20 %) et finalement hors rue (< 3 %) (Dalla Chiara et al., 2023).

Parmi les stratégies de gestion de la bordure de rue les plus répandues, on retrouve l'allocation d'espaces de livraisons, le partage de données, l'instauration de limites de temps de stationnement et leur application. D'après une revue méta de la littérature, l'allocation d'espaces de livraisons permet de réduire en moyenne de 25 % le temps de route des tournées de livraison (fortement lié à la recherche d'un stationnement), de 41 % les émissions du dernier kilomètre et finalement de 28 % le temps de livraison (Castrellon & Sanchez-Diaz, 2024).



Figure 2.2 Exemples de stationnements gênants à Amsterdam (Pays-Bas) (gauche) en bordure de trottoir et à Montréal (Canada) (droite) avec un camion en sortie de zone piétonne

Les activités de logistique urbaine requièrent des zonages adéquats. Tel que mentionné par Heitz (2020), la fonction logistique dans les villes est régulièrement mal identifiée, ce qui donne lieu à des défis de planification urbaine pour intégrer correctement ces fonctions logistiques. D'un côté, il existe un phénomène d'étalement logistique, dans lequel les activités logistiques sont repoussées en périphérie des grands centres urbains (Dablanc & Rakotonarivo, 2010; Heitz et al., 2017) et de l'autre un phénomène de logistique de proximité, dans lequel des fonctions logistiques font leur retour dans des espaces à zonage mixte au sein des villes afin de contrer les externalités financières et environnementales liées au dernier kilomètre (Buldeo Rai et al., 2022a). Une étude de cas sur les villes de Paris (France) et Rotterdam (Pays-Bas), deux villes meneuses en logistique urbaine, démontre que chaque ville doit établir des politiques sur mesure. De même, la planification urbaine

des villes ne peut plus se faire dans intégrer la planification de la logistique urbaine (Kin et al., 2024).

2.1.2 Les enjeux liés aux véhicules utilisés

Sans surprise, les activités de logistique urbaine, et encore plus les activités de livraison de marchandises sont d'importantes génératrices de GES et autres particules fines. Les stratégies d'atténuation de ces externalités négatives passent souvent par l'électrification massive des flottes de véhicules. En effet, l'électrification massive des flottes de camions légers, combinée avec le verdissement de la production d'électricité pour un contexte états-unien démontre que sur le court-terme, il y aurait des impacts bénéfiques pour la santé, particulièrement en ce qui a trait aux émissions de particules fines (Schmitt et al., 2024). Sur le long terme, c'est le verdissement de la production d'électricité qui aurait le meilleur impact sur la santé des populations locales (Schmitt et al., 2024).

Cependant, la substitution des véhicules thermiques par des véhicules à basses émissions carbones comme les vélos-cargos représente un potentiel intéressant. L'analyse de cycle de vie, menée en Italie, montre que le remplacement d'une camionnette au diesel par un vélo-cargo représente 250 g de CO_2 équivalent par kilomètre en moins. Le même exercice pour une camionnette électrique permet d'éviter 173 g de CO_2 équivalent / km (Temporelli et al., 2022).

L'ensemble des émissions liées aux activités de livraison sont amplifiées par la congestion routière. Une étude menée en Italie pendant la pandémie de COVID-19 a permis de mettre en avant les effets de la congestion sur la pollution atmosphérique. Sans surprise, les auteurs ont trouvé une corrélation entre congestion routière et augmentation des niveaux de NO, NO_2, et NOx[1], mais pas d'augmentation significative du niveau de PM_{10}[2] (Rossi et al., 2020).

Les activités de livraisons engendrent particulièrement de la pollution sonore. Alors que de nombreux articles en font mention en introduction générale sur la logistique du dernier kilomètre, après de nombreuses recherches menées, il n'existe pas de littérature scientifique spécifique sur la

[1] Les oxydes d'azote (NOx) contribuent notamment à la formation du smog et des pluies acides, ce qui impacte la santé respiratoire. Le dioxyde d'azote (NO_2) peut provoquer une inflammation des poumons en cas d'exposition à des concentrations élevées. Quant au monoxyde d'azote (NO), il peut entraîner divers problèmes de santé, tels que des nausées, une baisse de la pression artérielle et des troubles respiratoires (*All about NOx, NO and NO2*).

[2] Les particules fines PM_{10}, dont la taille est inférieure à 10 microns, peuvent pénétrer profondément dans les poumons (*Inhalable Particulate Matter and Health (PM2.5 and PM10) | California Air Resources Board*).

pollution sonore et les activités de livraisons. Ce pan de recherche permettrait de quantifier la pollution sonore et les réductions possibles en utilisant différentes stratégies de livraisons (substitution de véhicules, livraisons en heures décalées etc.).

2.1.3 Les enjeux liés à la nature du travail effectué

Tel que présenté dans une revue critique de la littérature par Strale (2019), les conditions de travail des personnes travaillant dans les métiers de la logistique urbaine sont peu considérées dans la littérature scientifique, bien que de nombreuses pratiques s'inscrivent dans une perspective de développement durable. Le constat de Strale (2019) corrobore les résultats de la revue de littérature menée par Wolpert & Reuter (2012), qui déjà montrait que sur 94 articles, seul 1 prenait en compte l'aspect des conditions de travail dans les articles de logistique urbaine. Dans le cadre spécifique des travaux de cette thèse, l'angle adopté est principalement sur les conditions de travail des cyclistes commerciaux. Les cyclistes commerciaux sont particulièrement exposés à des blessures inhérentes à leur activité professionnelle. L'analyse des blessures majeures à New-York entre 2008 et 2014 révèle sur 819 blessés cyclistes, 34,7 % d'entre eux exerçaient une activité rémunérée, avec une sur-représentation de la communauté latino-américaine parmi eux (Heyer et al., 2015). Bien que les cyclistes commerciaux aient souvent des blessures moins graves que les cyclistes récréatifs, seulement 39 % d'entre eux portaient un casque régulièrement. À travers des entrevues détaillées, Lachapelle et al. (2021) établit un cadre pour analyser les risques et les accidents rencontrés par les cyclistes commerciaux en analysant 21 facteurs répartis en quatre catégories : caractéristiques et traits individuels, type de travail et conditions de travail, niveaux d'exposition et les facteurs externes. Ce cadre d'analyse permet ainsi de développer des méthodes de sondage adéquates, prenant en compte ces quatre grandes catégories.

À partir de l'analyse des principaux enjeux de la logistique urbaine et de leur couverture dans la littérature, plusieurs pistes de recherche émergent. Celles-ci seront approfondies dans la suite de cette revue de littérature ainsi que dans les articles constituant cette thèse. La première question porte sur les leviers permettant de favoriser l'émergence et le déploiement des vélos-cargos, en particulier pour la ville de Montréal. Dans cette dynamique d'extension des initiatives de cyclologistique, se pose également la question de l'adaptation des modèles logistiques aux profils des villes, notamment dans les villes moyennes, dont les caractéristiques diffèrent des grandes métropoles. Par ailleurs, la littérature scientifique accorde encore peu de place aux travailleurs du

secteur des livraisons à vélo-cargo, alors même que leur activité les expose à divers risques, qu'ils soient liés aux infrastructures et/ou aux conditions météorologiques. Quelles sont leurs préférences en matière d'infrastructures et comment ces facteurs influencent-ils leur comportement sur la route ? Enfin, une autre question centrale concerne la place laissée par la ville aux initiatives de logistique domestique. Dans quelle mesure ces initiatives s'intègrent-elles aux dynamiques urbaines actuelles et quels défis restent à relever pour leur développement ?

2.2 Activités de livraison et vélos-cargos

L'essor des vélos-cargos dans le domaine de la logistique urbaine s'accompagne d'une transformation des pratiques de livraison, notamment dans le cadre du dernier kilomètre. Cette section examine les infrastructures et caractéristiques essentielles qui conditionnent l'efficacité de ces véhicules dans les réseaux de distribution. D'une part, les micro-hubs et centres de consolidation urbains jouent un rôle central en optimisant le transfert des marchandises vers des modes de transport plus adaptés aux environnements denses, mais leur mise en œuvre soulève des défis économiques et organisationnels. D'autre part, les performances des vélos-cargos varient selon leurs caractéristiques techniques, influençant directement leur capacité de charge, leur vitesse et leur intégration dans les opérations de livraison. Enfin, l'évaluation de leurs performances met en lumière des bénéfices environnementaux et économiques, tout en soulevant des enjeux liés à l'aménagement urbain, aux conditions de travail des livreurs et aux contraintes climatiques. Cette analyse permet ainsi de mieux cerner les leviers et obstacles à l'adoption des vélos-cargos dans un contexte logistique en pleine évolution.

2.2.1 Micro-hub et centres de consolidation urbains

Dans le cadre spécifique de la livraison par vélo-cargo, le micro-hub s'inscrit comme un élément clé de réussite du dernier kilomètre. Le micro-hub se définit comme un espace logistique de petite taille, situé à proximité des aires de livraison visées (Katsela et al., 2022). Les micros-hubs s'inscrivent dans la continuité des centres de consolidation urbains (CCU). En général, les CCU sont situés en périphérie des villes et sont des espaces logistiques plus grands et opèrent à une échelle plus large que les micros-hubs (Allen et al., 2012). Tel qu'identifié par Katsela et al. (2022), les termes micro-hubs, micro-dépôt et micro-centres de consolidation sont utilisés de manière interchangeable dans la littérature.

Il existe différents types de micro-hubs (Figure 2.3), selon les objectifs poursuivis et différents niveaux de collaboration et participation des différents acteurs (transporteurs, municipalités etc.). La première distinction qui peut être faite est entre les micros-hubs fixes et les micros-hubs mobiles.



Figure 2.3 Exemples de micro-hubs à Montréal (gauche : Colibri Iberville, droite: pôle de livraison Rosemont)

Les micros-hubs mobiles peuvent être des structures itinérantes, souvent des camions dont l'objectif est de servir de point de contacts pour remplir des véhicules plus petits (véhicules électriques légers ou encore vélos-cargos) (Marujo et al., 2018). Les micros-hubs mobiles peuvent être aussi une structure placée en bord de rue (Faugère et al., 2020; Verlinde et al., 2014). Ensuite, il est possible de différencier les micros-hubs partagés (par exemple l'hôtel logistique Beaugrenelle, en France (Sogaris), ou Colibri à Montréal (« Colibri Iberville »)) et des micros-hubs dédiés à une seule entité. Il est à noter que partage des espaces logistiques ne sous-entend pas nécessairement une mutualisation ou une consolidation des tournées de livraison.

Parmi les obstacles et enjeux principaux à la mise en place et pérennisation opérationnelle et financière des micros-hubs, on retrouve leur viabilité économique ainsi que leur financement. La rentabilité de ce type d'infrastructures est possible mais conditionnelle à une gestion optimale, difficile à obtenir dans des situations réelles (Janjevic & Ndiaye, 2017). Les coûts élevés et la difficulté d'obtenir des revenus stables et suffisants rendent la viabilité économique de ces lieux logistiques complexe (Janjevic & Ndiaye, 2017; van Heeswijk et al., 2019).

La gouvernance des micros-hubs demeure un enjeu. Le rôle et les responsabilités des parties prenantes doivent être correctement identifiés (Björklund & Johansson, 2018). La collaboration entre municipalités, entreprises de logistique et autres parties prenantes nécessite une coordination efficace pour assurer le bon fonctionnement et la durabilité des micro-hubs (Ambrosini et al., 2013; Gonzalez-Feliu et al., 2014; Nylander et al., 2023) .

Un autre enjeu est le manque de foncier logistique au sein des villes pour établir les micro-hubs urbains, ainsi que la présence des caractéristiques nécessaires (emplacement, accès à des camions plus grands, débarcadère pour vélos). En comparant les cas de logistique de proximité dans cinq villes hautement densifiées, Buldeo Rai et al. (2022b) mettent de l'avant que les initiatives de logistique de proximité s'approprient les caractéristiques des espaces urbains dans lesquelles elles prennent forme et sont ensuite façonnées par les différentes politiques publiques en place.

Ainsi, les micro-hubs apparaissent comme une solution prometteuse pour optimiser la logistique du dernier kilomètre, en particulier dans le cadre de la livraison par vélo-cargo. Cependant, leur mise en place et leur pérennisation se heurtent à plusieurs défis, notamment en termes de viabilité économique, de gouvernance et d'intégration dans l'espace urbain. Leur succès repose sur une collaboration efficace entre les acteurs impliqués et une adaptation aux contraintes spécifiques des environnements urbains.

2.2.2 Caractéristiques techniques des vélos-cargos

Il existe différents types de vélos-cargos (Figure 2.4), chaque type ayant ses caractéristiques propres.



Figure 2.4 Exemples de vélos-cargos

2.2.3 Les triporteurs (Figure 2.4, b, c, e)

Les vélos triporteurs, comme leur nom l'indique, sont munis de trois roues ce qui leur procure une plus grande stabilité. En général, le chargement est situé à l'arrière du vélo et directement maintenu au cadre du vélo (à la différence des vélos en attelage). Le chargement à l'arrière du vélo permet de ne pas obstruer la vision de l'opérateur (Stout & Kaddoura, 2021), lorsque le chargement est bas. Les triporteurs sont les vélos-cargos qui ont la plus grande capacité d'emport, autour de 250 kg pour Tipagornwong & Figliozzi (2014) et 272 kg pour Sheth et al. (2019) pour ce qui est des exemples tirés de la littérature scientifique. Les charges maximales sont spécifiées par les manufacturiers des vélos-cargos.

2.2.4 Les vélos à attelage (Figure 2.4, a, d, f)

Les vélos-cargos peuvent être un attelage d'une remorque avec un vélo classique (souvent avec assistance électrique). La remorque peut être soit avec une ouverture tombeau (Figure 2.4, d) ou une ouverture par l'arrière (Figure 2.4, b). Les vélos à attelage donnent une flexibilité dans la préparation des tournées pour la livraison. En effet, plusieurs chargements peuvent être préparés en amont afin de gagner du temps d'opération. Moins populaire en Amérique du Nord, l'utilisation

de la technologie « Bicylift » de l'entreprise Fleximodal (Figure 4, a) permet l'emport d'une palette taille européenne (1200 x 800 x 145 mm). Dans la littérature, les capacités d'emport des vélos-cargos diffèrent, allant de 80 kg (Nocerino et al., 2016) à 200 kg (Robichet et al., 2022). Un détail des capacités d'emport relevées dans la littérature par type de vélo-cargo est présenté au Tableau 2.1.

Certains vélos en attelage peuvent aussi avoir une place pour un chargement à l'avant. Les biporteurs à chargement avant présentent l'avantage d'être souvent plus étroits et donc plus manœuvrable, mais moins stables (Stout & Kaddoura, 2021). Un autre type de vélo-cargo est le vélo dit « long tail », peu utilisé dans le cadre de la cyclologistique mais particulièrement prisé des familles avec enfants. Pour indication, au Canada, le prix d'achat de ces vélos-cargos oscille entre 7 500 $ et 13 000 $ par unité selon les marques, tel que détaillé dans l'analyse de l'Institut Pembina (Stout & Kaddoura, 2021). Cette analyse proposée par l'Institut Pembina se base sur les prix de vente affichés et sans accessoires ni personnalisation des vélos-cargos.

Tableau 2.1 Capacité d'emport des vélos-cargos dans la littérature scientifique

Capacité d'emport (kg)	Vélo classique avec sac à dos ou panier	18.5 kg (Gonzalez-Calderon et al., 2022) 25 kg (Nocerino et al., 2016)
	Vélo-cargo biporteur (chargement avant ou arrière)	80 kg (Nocerino et al., 2016) 120 kg (Gonzalez-Calderon et al., 2022) Min. 50 kg (Narayanan et al., 2022) 164 kg (Koning & Conway, 2016) 180 kg (Hofmann et al., 2017) 250 kg (Fraselle et al., 2021) 200 kg (Robichet et al., 2022)
	Triporteur	250 kg (Tipagornwong & Figliozzi, 2014) 272 kg (M. Sheth et al., 2019)
Volume (m^3)	Vélo classique avec sac à dos ou panier	0.07 m^3 (Nocerino et al., 2016) 0.131 m3 (Gruber & Narayanan, 2019)
	Vélo-cargo biporteur (chargement avant ou arrière)	0.250 m3 (Nocerino et al., 2016) 0.187 m3 (Gruber & Narayanan, 2019) 0.304 m3 (Gruber & Narayanan, 2019) 1 m^3 (Hofmann et al., 2017; Melo & Baptista, 2017)
	Triporteur	2.18 m3 (M. Sheth et al., 2019) 1.3 m3 (Gruber & Narayanan, 2019)
Nombre de colis	Vélo classique avec sac à dos ou panier	_
	Vélo-cargo biporteur (chargement avant ou arrière)	10 colis (Arnold et al., 2018) 40 colis (Büttgen et al., 2021; Hofmann et al., 2018; Rolf et al., 2023)
	Triporteur	40 colis (M. Sheth et al., 2019)

Certaines études présentent la capacité d'emport en poids, d'autres en volumes ou encore en nombre de colis. Peu d'études comparent les performances de différents types de vélos-cargos entre eux, à l'exception de Nocerino et al. (2016). Une telle comparaison permettrait d'identifier le type de vélo-cargo le plus approprié selon les caractéristiques des biens à livrer, ou encore des caractéristiques inhérentes aux milieux dans lesquels ils opèrent.

Tout comme pour les poids et volumes, les vitesses relevées dans les études diffèrent fortement, quand elles sont mentionnées, allant de 11 km/h à 24 km/h. Les vitesses sont soit des vitesses moyennes réelles, ou bien des vitesses moyennes assignées dans les études de simulation (Tableau

2.2). Certaines études ne mentionnent aucunement la vitesse des vélos-cargos. Tout comme pour les poids, les vitesses moyennes ont été recalculées dans le système métrique.

Tableau 2.2 Vitesse moyenne observée ou assignée des vélos-cargos dans la littérature

Vitesse moyenne (km/h)	Vitesse moyenne observée (données GPS, observations, mesures)	11,10 km/h (conditions hivernales) et 15,33 km/h (conditions printannières) (Dybdalen & Ryeng, 2022) 11,6 km/h (Conway et al., 2017a) 15.9 km/h (Gruber & Narayanan, 2019) 16,3 km/h (hyper centre), 15,4 km/h (centre) et 16,1 km/h (périphérie) (Kale Ai, 2023) 19-21 km/h (Giordano et al., 2022) 24,1 km/h (M. Sheth et al., 2019)
	Vitesse moyenne assignée (données dérivées d'un autre mode de livraison, données par simulation)	12 km/h (Arnold et al., 2018) 12,96 km/h (Hofmann et al., 2018) 18 km/h (Büttgen et al., 2021)

La seule étude qui prend en compte les données hivernales est celle de Dybdalen & Ryeng (2022) en Norvège. Sans surprise, les vélos-cargos ralentissent lors des tournées hivernales. L'étude menée par l'entreprise Kale AI sur les données réelles de l'entreprise de livraison à vélo-cargo Urbike à Bruxelles permet d'obtenir des résultats de vitesse très précis, avec un zonage de l'hyper centre de Bruxelles (« Pentagone »), le centre et la proche périphérie (Kale Ai, 2023). L'utilisation de ce type de zonage au sein d'autres études permettrait de mieux calibrer les modèles de simulation.

2.2.5 Mesures de performance des vélos-cargos

Les recherches sur l'utilisation des vélos-cargos pour la livraison de colis ont connu un essor significatif ces dernières années, ces véhicules représentant une alternative prometteuse aux fourgonnettes et camions de livraison en milieu urbain. Leur flexibilité et leur fiabilité en font un atout pour les réseaux de distribution de proximité (Schliwa et al., 2015). L'étude des vélos-cargos s'est développée en plusieurs phases successives, la première ayant porté sur l'évaluation de leur potentiel et de leur compétitivité dans le transport de marchandises. Gruber et al. (2014) ont ainsi mis en évidence la faisabilité du recours aux vélos-cargos dans six villes allemandes, soulignant que l'acceptabilité de cette alternative dépend des caractéristiques personnelles des livreurs, de la perception favorable du public et d'une insatisfaction croissante quant à l'empreinte écologique

des modes de transport traditionnels. D'autres travaux ont insisté sur le rôle déterminant des autorités locales dans la mise en œuvre réussie de ces initiatives (Schliwa et al., 2015) et ont identifié divers facteurs influençant leur viabilité économique et logistique, notamment le poids et le volume des marchandises, la distance de livraison, la topographie urbaine et la présence d'infrastructures cyclables et de stationnement dédiées (Schliwa et al., 2015). Par ailleurs, Choubassi et al. (2016) ont démontré que l'utilisation des vélos-cargos pour le dernier kilomètre postal est économiquement optimisée par la présence d'infrastructures cyclables, de dépôts urbains et d'une densité de population élevée.

Dans le but de mieux intégrer les vélos-cargos dans les chaînes logistiques, plusieurs modèles économiques et solutions algorithmiques ont été développés. Tipagornwong & Figliozzi (2014) ont proposé un modèle de coût spécifiquement adapté aux vélos-cargos et aux véhicules motorisés, tandis qu'Anderluh et al. (2017) ont élaboré des politiques de distribution prenant en compte une flotte de vélos-cargos intégrés à une flotte de vans, avec une réduction des coûts et émissions lors de cette intégration. À partir de ces constats, les travaux suivants se sont concentrés sur l'évaluation de leur intégration dans les flottes existantes, notamment à travers des études de simulation permettant d'analyser les performances économiques et environnementales des différents scénarios de livraison. Arnold et al. (2018), en utilisant des données empiriques de la ville d'Anvers (Belgique), ont montré que le recours aux vélos-cargos peut réduire les coûts opérationnels de 40 %, bien que cela entraîne une augmentation des délais de livraison en raison de leur capacité limitée. Fikar et al. (2018) ont démontré que la consolidation des flux logistiques au sein de micro-hubs améliore la compétitivité des vélos-cargos, tandis qu'Elbert & Friedrich (2020) confirment ces résultats à travers une modélisation hybride des scénarios de livraison à Francfort. D'autres études ont souligné la rentabilité économique des vélos-cargos dans des contextes à forte densité urbaine, comme au Brésil (Leite Nascimento et al., 2020) et à Seattle (États-Unis) (M. Sheth et al., 2019).

En parallèle, la littérature s'est enrichie d'analyses portant sur les impacts environnementaux des vélos-cargos, notamment en matière de réduction des émissions polluantes (Conway et al., 2017a; Hofmann et al., 2018; Melo & Baptista, 2017), de congestion routière (Koning & Conway, 2016) et d'occupation de l'espace en bordure de rue (Conway et al., 2017a). Toutefois, si ces travaux permettent de mieux cerner les effets globaux de leur intégration, ils négligent souvent un aspect fondamental : la prise en compte des préférences et des contraintes des livreurs eux-mêmes. En

effet, bien que certains travaux aient identifié des déterminants psychologiques influençant l'acceptation de ces véhicules (Gruber et al., 2014), les études sur les conditions de travail des livreurs et leurs préférences en matière d'équipements, de confort ou de sécurité restent rares. Lachapelle et al. (2021) proposent un cadre d'analyse des facteurs qui influencent la sécurité au travail des cyclistes commerciaux, divisé en quatre grandes catégories : caractéristiques individuelles, type d'emploi et conditions de travail, niveaux d'exposition et facteurs externes. Entre autres, le travail à la commission durant les heures de pointes de la circulation et dans des quartiers denses apparait comme étant la recette parfaite pour des blessures liées à ce type de profession. L'expérience des cyclistes commerciaux ainsi que la mise en place de bonnes pratiques de santé-sécurité au sein des entreprises semblent au contraire aider à la réduction des accidents (Lachapelle et al., 2021). Plusieurs initiatives en santé et sécurité existent en Europe, notamment par la mise en place de cours en ligne gratuits, comme « *SafeLMD* » (*SafeLMD-Compétences Écologiques et de Sécurité Pour Les Travailleurs Dans Les Livraisons Urbaines Du Dernier Kilomètre à Vélo*). Cependant, dans la littérature scientifique, la notion de sécurité pour les vélos-cargos est abordée sous l'angle du transport de personnes, plus que du transport de marchandises. La revue de littérature proposée par Chatziioannou et al. (2024) infère aux vélos-cargos les facteurs déterminants de sécurité des cyclistes récréatifs. Seuls sept articles de journaux cités sur les trente-huit (~ 18 %) sélectionnés mentionnent explicitement la présence de vélos-cargos ou bien de cyclistes commerciaux, ce qui illustre le besoin de recherche supplémentaires et spécifiques pour les cyclistes commerciaux.

De même, les études sur l'aménagement des infrastructures urbaines adaptées aux vélos-cargos demeurent limitées, alors que leur efficacité dépend largement de l'existence de micro-hubs bien situés et adaptés (Rudolph et al., 2021; Katsela et al., 2022), de pistes cyclables larges (Rudolph & Gruber, 2017) ainsi que d'espaces de stationnement adaptés (Castrellon & Sanchez-Diaz, 2024; Rudolph & Gruber, 2017).

Enfin, un pan récent de la littérature s'intéresse aux défis spécifiques posés par l'environnement physique et climatique pour les opérations de vélos-cargos. Les études menées en Norvège ont mis en évidence les contraintes liées aux conditions hivernales et à l'usure accélérée des équipements (Dybdalen & Ryeng, 2022). Très peu de travaux prennent en compte des conditions climatiques défavorables à l'adoption des vélos-cargos pour le transport de marchandises. D'autres travaux ont analysé l'impact de la topographie et des conditions météorologiques sur l'énergie des cyclistes et

le besoin d'assistance électrique (Giordano et al., 2022; Gonzalez-Calderon et al., 2022). Ces résultats soulignent l'importance d'adapter la conception des vélos-cargos et des infrastructures associées à ces contraintes, d'autant plus que l'essor de nouvelles technologies pourrait accroître leur attractivité et leur facilité d'utilisation à l'avenir (Peppel et al., 2022).

Dans l'ensemble, bien que les performances économiques et environnementales des vélos-cargos soient désormais bien documentées, des lacunes persistent quant à l'intégration des préférences des livreurs et aux enjeux de santé et sécurité ainsi que la prise en compte des conditions géographiques des espaces dans lesquels ils œuvrent.

2.3 Mise à l'échelle des vélos-cargos

L'essor des vélos-cargos en tant que solution logistique durable ne se limite plus uniquement à la livraison du dernier kilomètre dans les métropoles. Leur potentiel s'étend désormais à des domaines plus larges, tels que la logistique des ménages et l'optimisation des flux de marchandises dans des contextes urbains variés, y compris les villes de taille moyenne. Cette section explore ces deux dimensions en mettant en lumière les opportunités qu'offre la micromobilité pour le transport des biens à l'échelle individuelle, ainsi que les défis liés à l'adoption du vélo-cargo au-delà des grands centres urbains. D'une part, la logistique des ménages représente une part non négligeable des livraisons en ville, influencée par les comportements de consommation et les nouvelles solutions de mobilité active. D'autre part, les villes moyennes, bien que moins étudiées, offrent un cadre propice à l'expérimentation et à l'intégration de ces solutions, nécessitant néanmoins des stratégies adaptées à leurs particularités territoriales et socio-économiques.

2.3.1 La logistique des ménages et micromobilité

Cette section sort du prisme de la livraison du dernier (ou premier) kilomètre et se concentre sur le concept de logistique des ménages (« *household logistics* » ou « *household freight* »). L'impact des ménages dans la production de trajets de livraison n'est pas à sous-estimer. En Belgique, un quartier est traversé en moyenne 3,6 fois par jour par des services de livraison (Beckers et al., 2022), tandis qu'à Montréal, la population de la région métropolitaine de Montréal reçoit 0,26 colis par jour, soit environ 900 000 livraisons quotidiennement (Meloche et al., 2025). Le comportement des consommateurs, dicté notamment par leurs attributs socio-démographiques, influencent particulièrement le nombre de livraisons à domicile. Sans surprise, un revenu médian élevé ainsi

qu'un haut niveau d'éducation accroissent la probabilité d'achats en ligne (Beckers et al., 2022), avec une large proportion des achats dédiés aux articles de mode et articles électroniques (> 70 % des achats) (Beckers et al., 2022). Cependant, les consommateurs manifestent une volonté de changer leurs pratiques afin de rendre les livraisons plus durables. Buldeo Rai et al. (2018) démontrent que les consommateurs sont prêts à aller chercher eux-mêmes ou attendre plus longtemps leur colis si la livraison et le retour sont gratuits. De même, lorsque les consommateurs détiennent l'information sur l'impact environnemental de leur livraison, ils choisissent la livraison dont les impacts sont moindres (Ignat & Chankov, 2020). Selon le type de produits commandés, les consommateurs sont prêts à faire plus ou moins de concessions sur l'aspect environnemental (Nogueira et al., 2021). Cependant, il existe très peu de littérature, autre que la branche de littérature sur le logistique inversée, qui met le consommateur dans une position active vis-à-vis des activités de livraison du dernier kilomètre. C'est ce que l'article sur les déterminants du succès des remorques à vélos à Bruxelles et Montréal tente de combler, avec l'apport d'une solution de micromobilité issue d'initiatives citoyennes, appliquée à la logistique des consommateurs.

La micromobilité est une branche de la littérature encore récente mais en pleine croissance, qui s'intéresse à l'utilisation de micros-véhicules (Oeschger et al., 2020). Les différentes définitions de la micromobilité convergent vers des véhicules dont la masse est inférieure à 350 kg, la vitesse inférieure à 45 km/h et dont l'utilisation est faite sur des courtes distances (International Transport Forum, 2020). Dans le cadre de cette définition, les remorques à vélo en attelage avec un vélo régulier se qualifient comme solution de micromobilité dans le cadre de la micromobilité. Les études actuelles en micromobilité se concentrent régulièrement sur la connectivité avec les réseaux de transport structurant (Oeschger et al., 2023) et la substitution à d'autres modes de transport, notamment la voiture particulière (Bösehans et al., 2024a) ou même au transport public (Campbell et al., 2016). Au meilleur des recherches menées, il n'y pas encore d'articles qui couvrent l'utilisation d'une solution de micromobilité pour le transport des marchandises dans le cadre de la logistique des ménages.

2.3.2 Sortir du prisme des métropoles

La majorité des études portant sur les vélos-cargos s'inscrit dans un contexte urbain marqué par une forte densité de population. Les recherches menées sur ce sujet se concentrent principalement sur des villes telles que Paris (Giordano et al., 2022; Koning & Conway, 2016; Robichet et al.,

2022), Vienne (Anderluh et al., 2017), Anvers (Arnold et al., 2018), ou encore Rio de Janeiro, Medellin et d'autres villes sud-américaines (Gonzalez-Calderon et al., 2022; Leite Nascimento et al., 2020; Marujo et al., 2018). En Amérique du Nord, des travaux ont été réalisés à New York (Conway et al., 2017a), Seattle (M. Sheth et al., 2019), Austin (Choubassi et al., 2016) et Montréal (Lachapelle et al., 2021).

D'une manière générale, le choix d'un contexte géographique spécifique vise soit à illustrer l'application d'une solution ou d'une méthode développée dans une étude, soit à analyser les spécificités locales influençant l'usage des vélos-cargos. Par exemple, Büttgen et al. (2021) et Hofmann et al. (2018) testent leurs solutions respectives de problème de routage de véhicules et de simulation multi-agents dans les villes d'Innsbruck (Autriche) et de Grenoble (France). De la même manière, Conway et al. (2017) et Sheth et al. (2019) comparent différents modes de transport dans les contextes urbains de New York et Seattle. En revanche, certaines études s'intéressent aux villes en tant qu'objets d'analyse en elles-mêmes, en examinant l'impact de leurs caractéristiques sur l'usage des vélos-cargos, comme le montrent les travaux de Giordano et al. (2022), Gonzalez-Calderon et al. (2022) et Dybdalen & Ryeng (2022).

Toutefois, un décalage persiste entre les recherches mobilisant un cadre géographique à des fins d'expérimentation méthodologique et celles qui explorent directement l'influence des spécificités urbaines sur l'usage des vélos-cargos. C'est dans cette perspective que s'inscrit l'étude des villes moyennes au Québec, qui vise à combler cette lacune en développant une méthodologie permettant de les classifier en fonction de leurs caractéristiques et d'adapter les stratégies d'adoption du vélo-cargo en conséquence. Dans le contexte québécois, Rochefort et al. (2023) proposent une approche multicritère pour mieux appréhender les différences entre les villes et planifier des politiques publiques spécifiques.

Les villes de taille moyenne présentent des enjeux spécifiques en matière de logistique urbaine. L'intégration stratégique du transport de marchandises dans leur développement demeure encore limitée (Flora et al., 2019), bien que certaines, confrontées à une croissance économique plus faible, manifestent un intérêt accru pour la mise en place de solutions logistiques visant à améliorer l'efficacité de leur réseau de transport (De Marco et al., 2018). La configuration de ces villes se caractérise par des distances de livraison plus courtes (Delaitre et al., 2009) et une organisation sociale qui permet une meilleure visibilité des flux de marchandises. Cette particularité facilite

l’implication des parties prenantes et l’expérimentation de solutions innovantes en logistique urbaine (Delaitre et al., 2009). Dans ce cadre, le recours aux vélos-cargos pour la distribution des marchandises apparaît comme une opportunité pertinente, susceptible de répondre aux défis logistiques de ces espaces intermédiaires.

CHAPITRE 3 DONNÉES ET MÉTHODOLOGIE GÉNÉRALE

Ce chapitre présente les approches méthodologiques et les sources de données mobilisées pour analyser le rôle des vélos-cargos et des solutions de micromobilité en logistique urbaine. À travers les quatre articles qui constituent de cette thèse, il met en lumière les différentes échelles d'analyse adoptées, allant de l'étude d'une initiative locale de livraison à vélo-cargo à Montréal jusqu'à une réflexion plus large sur le potentiel de ces solutions dans les villes de taille moyenne et les services de remorques à vélo partagées. La diversité des méthodes employées dont des analyses statistiques, enquêtes de terrain, captations vidéo et traitement de données géospatiales, permet d'examiner les déterminants de l'adoption et du fonctionnement de ces alternatives logistiques sous différents angles, contribuant ainsi à une meilleure compréhension des conditions nécessaires à leur déploiement efficace et pérenne.

3.1 Cadre méthodologique général

Les quatre articles de cette thèse s'articulent autour d'une exploration approfondie du rôle du vélo-cargo et des solutions de micromobilité dans la transformation des systèmes de logistique urbaine. L'analyse débute avec l'étude du déploiement spontané d'une initiative de livraison à vélo-cargo à Montréal en réponse aux bouleversements provoqués par la pandémie de Covid-19. Ce contexte exceptionnel a permis de tester les vélos-cargos comme mode de livraison, démontrant leur potentiel en tant qu'alternative crédible aux véhicules motorisés pour la logistique urbaine. Ainsi, cette première étude constitue une preuve de concept du vélo-cargo comme solution viable pour la livraison du dernier kilomètre, en mettant en évidence les facteurs influençant son adoption.

Le deuxième article approfondit cette dynamique en explorant les défis opérationnels des livraisons réalisées avec des vélos-cargos, notamment l'influence des infrastructures cyclables, des conditions météorologiques et la prise en compte des préférences des livreurs à vélo-cargo. L'étude met en évidence les aspects sous-estimés au niveau de la livraison (stratégies de stationnement, organisation du vélo-cargo etc.) qui peuvent avoir un impact sur la performance de ce mode de livraison.

Le troisième article marque un changement d'échelle en élargissant la réflexion à la pertinence des vélos-cargos dans des villes de taille moyenne, jusqu'alors peu étudiées. En s'appuyant sur des méthodes quantitatives et des analyses multicritères, cette étude met en évidence les conditions

favorables à leur intégration en fonction de la densité urbaine, des infrastructures cyclables et des caractéristiques du tissu urbain. Ce passage d'un cadre de métropole à une analyse basée sur les caractéristiques des villes permet de mieux cerner les contextes dans lesquels la cyclologistique peut être efficacement déployée au-delà des grandes agglomérations.

Enfin, le quatrième article ouvre la perspective vers une solution de micromobilité partagée, en analysant l'usage des remorques à vélo en libre-service et leur potentiel en tant qu'alternative aux véhicules motorisés pour le transport de marchandises en milieu urbain pour les ménages. Cet article illustre également un transfert de connaissances entre les travaux effectués précédemment sur la cyclologistique à destination des entreprises et une initiative citoyenne, marquant ainsi un élargissement des applications possibles de ces solutions de transport durable.

3.2 Démarche méthodologique

La section 3.2 présente les méthodologies adoptées dans les articles scientifiques qui composent cette thèse. À travers une combinaison d'analyses statistiques, d'enquêtes de terrain et de traitements de données géographiques, ces études explorent les déterminants du succès des livraisons à vélo-cargo et des services de remorques partagées. L'objectif est de croiser différentes sources d'information pour mieux comprendre les dynamiques spatiales, socio-économiques et infrastructurelles qui influencent l'adoption de ces solutions de transport durable en milieu urbain.

3.2.1 Article 1 : analyse statistique multi-niveaux

La méthodologie adoptée dans cet article repose sur une analyse statistique multi-niveaux visant à examiner les facteurs influençant le succès d'une initiative de livraison urbaine par vélos cargo à Montréal durant la première vague de la pandémie de Covid-19. La collecte de données s'est déroulée sur une période de 16 semaines, de mars à juillet 2020, couvrant un total de 6 713 livraisons effectuées par 44 livreurs pour 91 commerces participants. Ces données ont été enrichies par l'intégration d'informations complémentaires provenant de sources officielles, notamment des indicateurs socio-démographiques, des conditions météorologiques et des statistiques sur l'évolution de la pandémie. L'analyse repose sur un modèle de régression linéaire multi-niveaux permettant de tenir compte de la structure hiérarchique des données, avec des variables explicatives à plusieurs niveaux : les caractéristiques des commerces (niveau 2) et les paramètres spécifiques aux livraisons (niveau 1). Ce cadre méthodologique a été choisi afin d'identifier les interactions

entre les déterminants de la demande en livraison et les conditions exogènes, tout en capturant les effets temporels liés à l'évolution de la pandémie. L'implémentation du modèle a suivi une approche progressive en quatre étapes : un modèle nul servant de référence, suivi de l'introduction des variables temporelles, puis des caractéristiques des commerces, et enfin des facteurs socio-économiques des quartiers de livraison. L'ajustement du modèle a été évalué à l'aide des critères AIC (*Akaike information criterion*) et BIC (*Bayesian Information Criterion*), et la pertinence des variables a été testée selon leur significativité statistique. Cette approche a permis d'identifier des facteurs clés influençant le volume des livraisons, notamment la présence de publicité pour le service, la taille du ménage, l'âge moyen des consommateurs et les conditions météorologiques.

3.2.2 Article 2 : enquête auprès des livreurs et création de données

L'article 2 repose sur une approche méthodologique empirique visant à combler les lacunes existantes dans la littérature sur la livraison par vélo-cargo. À travers une enquête approfondie auprès des livreurs et la création de nouvelles données empiriques, l'objectif est d'analyser les dynamiques d'usage des infrastructures cyclables et les conditions de travail des livreurs dans un contexte urbain. La méthodologie s'articule autour de plusieurs sources de données complémentaires : un questionnaire diffusé auprès des livreurs, des entretiens en situation de travail, des enregistrements vidéo et des relevés GPS. L'enquête par questionnaire a été conçue pour recueillir des informations sur les conditions de travail, les préférences en matière d'infrastructures et les risques perçus par les livreurs. Elle a été administrée auprès d'un échantillon des livreurs à vélo-cargo à Montréal, offrant un aperçu détaillé des contraintes et des défis rencontrés par ces travailleurs. Les entretiens, réalisés en immersion lors des tournées de livraison, ont permis d'observer en temps réel les stratégies adoptées par les livreurs en matière de choix d'itinéraires, d'organisation des cargaisons et de gestion des échecs de livraison. Cette méthode d'observation directe apporte une perspective sur la prise de décision en situation réelle, enrichissant ainsi les données recueillies par le questionnaire. Les enregistrements vidéo, réalisés à l'aide de caméras portées par les livreurs ou montées sur leurs vélos, ont documenté les interactions avec l'environnement urbain, les infrastructures et les autres usagers de la route. Ces enregistrements fournissent une documentation visuelle précieuse sur les conditions de circulation et les stratégies d'adaptation des livreurs. Enfin, les relevés GPS ont permis d'analyser les itinéraires réellement empruntés, la vitesse moyenne, les distances parcourues et l'utilisation effective des infrastructures cyclables. L'exploitation de ces données permet de quantifier avec

précision les parcours des livreurs et de mieux comprendre leur relation avec l'environnement urbain.

3.2.3 Article 3 et article 4 : fusion de sources de données et *clustering*

L'article sur les villes moyenne (article 3) ainsi que l'article sur les remorques partagées (article 4) présentent des similarités dans les méthodologies employées, d'où une présentation commune. Les deux articles s'appuient sur des données géographiques, sociodémographiques et d'usage des sols. Concernant l'usage des sols, les deux études intègrent une analyse détaillée du zonage urbain afin d'identifier les environnements propices à l'usage des vélos-cargos et des remorques. L'étude sur les remorques partagées met en évidence l'impact des zones résidentielles et commerciales sur la fréquence des prêts, révélant que ces types de zones génèrent des besoins en transport de marchandises pour les ménages. De même, l'article sur l'utilisation de vélos-cargos dans les villes moyennes examine la distribution de l'occupation des sols pour comprendre le potentiel d'implantation de services de livraison alternatifs dans ces villes.

Les méthodes de clustering jouent un rôle clé dans les deux articles pour catégoriser les usages et identifier des tendances selon le contexte urbain. L'étude sur les remorques partagées applique une classification en grappes (k-medoid) afin d'identifier des profils d'utilisation basés sur des indicateurs tels que le temps et la distance des trajets, ainsi que la proximité aux infrastructures de transport. L'article sur les vélos-cargos dans les villes moyennes, quant à lui, emploie une classification hiérarchique ascendante pour segmenter ces villes en fonction de leur potentiel d'adoption des vélos-cargos. Ce processus repose sur des critères tels que la densité de population, la diversité du zonage et la qualité des infrastructures cyclables, enrichis par un score pondéré basé sur un panel d'experts. Ces approches permettent dans les deux études de formuler des recommandations adaptées aux spécificités des environnements analysés, renforçant la pertinence des solutions de cyclologistique pour le transport urbain de marchandises.

3.3 Données utilisées

La section 3.3 présente les différentes sources de données mobilisées pour analyser la cyclologistique urbaine à Montréal, à Bruxelles ainsi que pour les villes moyennes. Les sous-sections détaillent notamment les données de l'initiative « livraison arc-en-ciel », le sondage auprès des livreurs, les enregistrements vidéo, les traces GPS, ainsi que des données sur l'utilisation des

sols et les remorques partagées. Toutes les sources de données ne sont pas utilisées dans tous les articles.

3.3.1 Données de l'initiative « livraison arc-en-ciel »

Dans le cadre du premier article sur la pandémie de Covid-19 et livraisons à vélo-cargo, la collecte de données a été réalisée par la coopérative de solidarité Coop Carbone et l'organisme Jalon Montréal. Les deux organismes ont colligé l'ensemble des données dans une base de données principale. Cette base de données comprend 6 713 livraisons effectuées par vélos cargo à Montréal entre mars et juillet 2020, couvrant une période de 102 jours. Chaque enregistrement inclut des informations détaillées sur l'origine et la destination des livraisons, les horaires d'appel et de collecte, ainsi que l'identification des livreurs. Cette base a été enrichie par l'intégration de données complémentaires issues de plusieurs sources afin de mieux contextualiser l'analyse. Les caractéristiques des commerces participants ont été prises en compte, notamment la présence d'un site transactionnel, l'utilisation de publicité sur les réseaux sociaux et l'appartenance à une initiative locale de promotion des achats via les sociétés de développement commercial (SDC). En effet, chaque SDC n'avait pas nécessairement la même approche pour promouvoir la livraison par vélo-cargo. En parallèle, des variables socio-démographiques ont été intégrées, incluant le revenu médian, la densité de population et la composition des ménages aux adresses de livraison, sur la base du recensement canadien de 2016. L'étude s'appuie également sur des indicateurs temporels liés aux restrictions gouvernementales imposées durant la première vague de la pandémie, ainsi que sur des données météorologiques portant sur la température extérieure et les précipitations quotidiennes. Enfin, la distance Euclidienne entre chaque point d'origine et de destination a été calculée pour évaluer son impact sur la dynamique des livraisons. La combinaison de ces différentes sources permet ainsi de proposer une analyse approfondie des déterminants influençant le succès de cette initiative de livraison urbaine en contexte de crise sanitaire.

3.3.2 Sondage auprès des livreurs

L'enquête par questionnaire menée dans le cadre de l'article 2, qui porte sur les interactions avec les infrastructures et les préférences des livreurs, vise à recueillir des données sur les conditions de travail, les préférences vis-à-vis des infrastructures et les défis rencontrés par les livreurs utilisant des vélos-cargos à Montréal. Administrée entre octobre et novembre 2022, l'enquête s'adresse aux livreurs impliqués dans la livraison du dernier kilomètre, à l'exclusion des coursiers de repas, dont

les pratiques diffèrent en raison de la nature de leur travail. Un total de huit participants ont répondu au questionnaire, représentant environ 30 % de la population cible estimée. Les répondants sont principalement des salariés, ainsi qu'un travailleur autonome, ce qui ne reflète pas l'ensemble de la diversité des statuts d'emploi dans le secteur de la livraison à vélo, notamment en ce qui concerne les livreurs travaillant pour des plateformes numériques ou à contrat précaire, qui n'étaient pas inclus dans cette étude. Afin d'assurer l'accessibilité et d'optimiser le taux de réponse, le questionnaire a été proposé en français et en anglais et complété en format papier, une approche souvent plus efficace que les enquêtes en ligne dans ce type de contexte.

Le questionnaire couvre plusieurs thématiques : les caractéristiques et besoins en maintenance des vélos-cargos, les conditions météorologiques et leurs impacts sur le travail, les préférences en matière d'infrastructures cyclables, les contraintes organisationnelles du travail et les risques perçus par les livreurs. Une section spécifique était également consacrée aux enjeux de santé et sécurité au travail, incluant les accidents, quasi-accidents et douleurs musculo-squelettiques associées à l'effort physique prolongé. Les résultats révèlent une grande variabilité des pratiques et perceptions en fonction de l'expérience des répondants, laquelle s'étendait de moins d'un an à plus de cinq ans dans le secteur.

3.3.3 Vidéos

Dans le cadre l'article 2, une série d'enregistrements vidéo a été réalisée afin de documenter de manière détaillée les pratiques et enjeux rencontrés par les livreurs à vélo-cargo à Montréal. Ces enregistrements, effectués en avril 2023 sur une période de quatre jours, ont permis de capturer les interactions des livreurs avec l'environnement urbain, les infrastructures cyclables et les autres usagers de la route. Plusieurs livreurs ont été équipés de caméras sportives (type *GoPro*), installées soit sur leur poitrine, soit sur le guidon de leur vélo-cargo, afin de varier les perspectives et d'obtenir une vision globale des défis rencontrés lors des livraisons. Une personne de l'équipe de recherche a aussi effectué des captations vidéos, permettant d'obtenir un point de vue extérieur. Ces différentes perspectives ont permis de croiser les observations et d'obtenir une vision plus fine des comportements et des contraintes vécues par les livreurs. Par exemple, les enregistrements en première personne ont révélé les ajustements effectués en temps réel par les livreurs pour naviguer dans le trafic urbain ou éviter des obstacles, tandis que les captations externes ont permis d'étudier les stratégies de stationnement et d'interaction avec l'espace public. De plus, les vidéos ont permis

d'analyser plusieurs aspects cruciaux du travail des livreurs : les stratégies de chargement et de déchargement des marchandises dans le caisson du vélo-cargo, les difficultés liées au stationnement et aux infrastructures, ainsi que les interactions avec les piétons et les véhicules motorisés. En complément, un membre de l'équipe de recherche a accompagné les livreurs durant trois des quatre journées de captation, afin d'effectuer des observations in situ et de recueillir des explications en temps réel sur leurs prises de décision. L'exploitation de ces vidéos a nécessité un travail de post-traitement important, notamment pour anonymiser les données sensibles telles que les adresses de livraison ou les codes d'accès. Il convient toutefois de souligner que cette collecte vidéo s'inscrit dans une démarche exploratoire, en raison du nombre limité de journées observées et de participants. Par ailleurs, les périodes couvertes par les différentes sources de données du projet (questionnaires, GPS, vidéos) ne coïncident pas entièrement, ce qui peut limiter la comparabilité directe entre les analyses. L'ensemble des données doit donc être interprété avec prudence, en tenant compte de ces contraintes méthodologiques.

3.3.4 Données GPS

Les données GPS collectées dans l'article 2 offrent un portrait des itinéraires empruntés par les livreurs à vélo-cargo à Montréal et permettent de qualifier leur utilisation des infrastructures cyclables. Entre juin 2021 et décembre 2022, 108 traces GPS ont été récoltées sur les profils de trois participants volontaires, chacun utilisant l'application sportive *Strava* pour documenter leurs trajets de livraison. Ces données, collectées exclusivement auprès de livreurs professionnels et anonymisées pour garantir la confidentialité des participants, fournissent des informations précises sur les distances parcourues, les vitesses moyennes, les temps de déplacement et l'élévation des trajets. L'ensemble des traces GPS collectées émettent à une fréquence d'un point par seconde. Cette fréquence élevée génère un grand nombre de points, ce qui permet d'obtenir une précision satisfaisante dans l'analyse des trajets. De légères pertes de données dues à des problèmes de connexion ne sont donc pas problématiques, car la densité des enregistrements compense ces interruptions ponctuelles. Bien que toutes les données soient regroupées sur la même application, elles ne sont pas enregistrées avec un même appareil : chaque livreur utilise son téléphone personnel pour enregistrer ses activités Strava. Cette hétérogénéité des dispositifs peut entraîner de légères variations dans la qualité des données GPS.

Le traitement des données GPS a demandé d'effectuer des corrections, afin de remettre les points GPS dans leur trajectoire initiale à la suite d'une perturbation causée par l'environnement bâti (exemples de la Figure 3.1).



Figure 3.1 Exemples de perturbations des traces GPS (gauche) à cause de l'environnement bâti (droite)

3.3.5 Données d'utilisation des sols

Les données d'utilisation des sols se retrouvent dans l'article sur les remorques partagées (article 4) ainsi que dans l'article sur le potentiel des villes moyennes (article 3) à recevoir des initiatives de cyclologistique. Dans le cadre de l'article sur les remorques à vélo, un arrimage entre les données de la ville de Bruxelles et celles de Montréal était nécessaire. Pour Bruxelles, ce sont les données issues du cadastre qui ont permis de classifier l'usage prépondérant du bâtiment. À Montréal, le gouvernement du Québec fournit une base de données d'utilisation des sols exhaustive. L'usage prépondérant est classé en différentes catégories (zonage résidentiel, commercial, industriel, services etc.) et chaque code correspond à une utilisation précise. Les résultats de l'article sur les remorques partagées mettent en évidence que les zonages résidentiels et mixtes sont les plus propices à l'adoption du service. Dans l'article sur les villes moyennes, les

données d'utilisation des sols permettent notamment de calculer un indice d'entropie de Shannon permettant de calculer la mixité de l'usage des sols, au sein d'hexagones de 500m (pour une superficie de 0,22 km^2).

3.3.6 Données sur les remorques partagées

Les données pour les remorques partagées proviennent de LocoMotion (Montréal) et Remorquable (Bruxelles). Ces données incluent les informations relatives aux prêts de remorques, telles que la date et la durée d'emprunt, la localisation des stations de dépôt, ainsi que des déclarations utilisateurs sur la distance parcourue et la nature des charges transportées. À Montréal, les utilisateurs renseignent librement l'usage fait de la remorque dans un champ textuel, tandis qu'à Bruxelles, une classification préétablie permet d'identifier les principaux motifs de prêt, comme les déménagements, les courses alimentaires ou le transport d'outils. Des variables liées à l'environnement issues de sources ouvertes permettent de mieux contextualiser l'étude, telles que la densité de population, l'accessibilité aux infrastructures de transport et la répartition du zonage urbain dans un rayon de 800 mètres autour des stations. À partir de ce jeu de données bonifiées, il est possible de dégager des tendances d'usage selon les caractéristiques sociodémographiques et spatiales des quartiers étudiés et d'analyser l'influence de l'environnement urbain sur la demande en remorques partagées.

CHAPITRE 4 ARTICLE 1 : « CHARACTERIZATION OF A COVID-FIRED URBAN BIKE DELIVERY SYSTEM : THE MONTREAL EXPERIENCE »

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CHARACTERIZATION OF A COVID-FIRED URBAN BIKE DELIVERY SYSTEM:
THE MONTREAL EXPERIENCE

Suzanne Pirie, Martin Trépanier, Walter Rei

4.1 Abstract

The Covid-19 pandemic led to a rapid change in consumers' demand for home deliveries and traditional delivery modes were unable to deliver consumers and shops due to the sudden increase in demand. This study investigates the results of a local cargo bike delivery initiative in Montreal, Canada, during the forced closure of non-essential businesses from March to May 2020. The objective of this study is to identify the variables which interacted with the performance of a cargo bike delivery initiative while considering the specific context of the Covid-19 pandemic. To assess such changing conditions, a multilevel linear regression analysis is carried out. This analysis allows to quantify the number of home deliveries while considering the impact of the number of active Covid-19 cases and sociodemographic predictors on the cargo bike initiative. The dataset covers 6,700 deliveries made by cargo bikes in the city of Montreal over 16 weeks. The results show that the presence of advertising and the characteristics of consumers' households, such as a smaller household size and a younger average age are amongst the strongest factors for the success of such initiative. The specific context of the Covid-19 pandemic allowed a better penetration of cargo bikes within the last-mile ecosystem.

Keywords: cargo bike; Covid-19; last-mile delivery; parcel delivery; multilevel analysis

4.2 Introduction

Good distribution played an important part during the first wave of the Covid-19 (February to July 2020) pandemic in Quebec, Canada. While consumers turned to online shopping for their purchases, logistics providers were dealing with delivery delays and supply chain issues. For example, during the first wave of the pandemic, Canada Post was unable to meet its deadlines in 37% of parcels sent (*Postes Canada*, 2020). As stated by Zhu et al. (2020), issues faced during the pandemic include supply and demand shocks, bullwhip effect and transportation requirements. The scope of this study focuses on the later as an initiative of cargo bike deliveries was developed in Montreal to help with freight transportation.

Cargo bike delivery systems are not new and have received acute attention from researchers with comprehensive studies by Narayanan & Antoniou (2022) on the current state of the art and Peppel et al. (2022) on the future of cargo bikes in cities. More specifically, the research on cargo bike often calls for practical case studies. Such case studies include the simulation of adding cargo bikes to the existing fleet of vehicles (Arnold et al., 2018; Elbert & Friedrich, 2020; Llorca & Moeckel, 2020), impacts of cargo bikes on one or several specific externalities related to the transport of goods (Büttgen et al., 2021; McLeod et al., 2020) and network designs including cargo bikes (Gil et al., 2023; Papaioannou et al., 2023; Robichet et al., 2022).

The delivery initiative presented in this study is based only on cargo bikes and is the result of the successful collaboration of the public and private sectors. Furthermore, this case study covers the first wave of the pandemic in Montreal, Quebec, Canada and is based on delivery data collected day-to-day, as the initiative grew and transformed with time. Indeed, several cargo bikes companies collaborated within days of the beginning of the pandemic with the city of Montreal and independent companies, to ensure that small independent shops that were closed due to the pandemic's restrictions could benefit from fast deliveries to their customers at a fair price. The bike delivery initiative focused on local deliveries, usually within a 5 km range from the shops from which the deliveries originated.

The objective of this paper is to identify interactions between the deliveries that are done during the initiative and the characteristics of participating shops (e.g., transactional website, advertisement etc.), customers (e.g., population density, median income at destination) and delivery conditions (e.g., weather) while considering the effects of Covid-19 restrictions. This

study is based on a short-term experimental set-up and thus contributes to the existing literature on cargo bikes as an experimental contribution in which only cargo bikes are considered as the delivery mode. To this aim, the delivery data is combined with other sources of data and used to perform a multi-level analysis. This method ensures the proper treatment of nested data structures and the proper identification of explanatory variables at the right levels (Bagley & Mokhtarian, 2002).

The results from this study identify certain factors that have an impact on the number of deliveries done for each participating shop, as well as some insights on the underlying behaviour of consumers back in the first wave of the pandemic of Covid-19.

4.2.1 First wave of Covid-19 in Quebec, Canada

In Quebec, Canada, the government declared the temporary closure of schools and universities on March 13th, 2020. Essential businesses (e.g., pharmacies, grocery shops, banks, hospitals etc.) were kept open but non-essential businesses (e.g., libraries, bookshops, clothing stores etc.) were closed on March 24th, 2020. An updated list of essential services was published regularly by the government of Quebec. To guarantee a basic level of service, kerbside pickups and orders were permitted with stringent distancing restrictions in place. People were asked to limit their social interactions to prevent the propagation of the virus. This measure was lifted gradually when the number of cases diminished, and the city of Montreal was the last to reopen its non-essential businesses on May 25th, 2020, in the province of Quebec. A short summary of the timeline of Covid-19 restrictions is provided in Table 4.1.

Table 4.1 Timeline of Covid-19 measures in Quebec, Canada (Ligne du temps COVID-19 au Québec | INSPQ, 2022)

Date	Covid-19 event
2020-02-25	Beginning of the first wave of Covid-19
2020-02-27	First case detected in Quebec of Covid-19
2020-03-13	Health emergency is declared by the government of Quebec
2020-03-18	First death due to Covid-19
2020-03-24	All non-essential businesses are closed to the public (restaurants, bookshops, etc.)
2020-05-04	Reopening of all non-essential businesses except for the Greater Montreal region.
2020-05-25	Reopening of all non-essential businesses for the Greater Montreal region
2020-07-18	End of the first wave of Covid-19

A report by Bilodeau et al. (2021) published for Statistics Canada shows that 21% of Canadians ordered groceries online for delivery or pickup. Among them, 13% made their first-time purchase online during the first wave of the pandemic. Also, 45% of Canadians reported purchasing more online than before the pandemic, according to the same authors. The pandemic also induced a modal shift to private vehicles from public transport and people were more likely to travel to shop than for work or education purposes (Abdullah et al., 2020; De Vos, 2020). However, the vulnerable populations became more dependent on home deliveries to meet their day-to-day needs, and last-mile delivery strategies needed to be adapted to serve these populations (Jones et al., 2021). A report published by Statistics Canada indicated that small businesses encountered greater constraints when compared to larger businesses in securing external financing during the initial phase of the pandemic (Government of Canada, 2022). Approximately half of the surveyed business owners reported experiencing cash flow difficulties. The same report revealed that approximately 20% of businesses anticipated that fluctuations in customer demand and purchasing patterns would pose a significant challenge within the next three months, representing one of their primary concerns.

4.2.2 Structure of the article

The rest of this paper is organized as follows. In Section 4.3, we present a literature review which includes a description of the evolution of the retail landscapes since the pandemic and a short review of cargo bike studies. The methodology described in Section 4.4 covers data collection and preparation, the presentation of the model and its formulation, assumptions, and implementation. As this analysis requires a certain level of context to be understood, the case study based on the city of Montreal is presented in Section 4.5. In Section 4.6, we present the results of our analysis, identifying the variables that are differentiated by importance in the model. Finally, in Section 4.7, some concluding remarks are made and potential avenues for future research are identified.

4.3 Litterature review

The literature presented in section 4.3 covers the changes observed in retail landscapes and physical movements since Covid-19 and the use of cargo bikes for last-mile deliveries in the literature.

4.3.1 Changes in retail landscapes and physical movements since Covid-19

The emergence and growth of e-commerce have significantly redefined the movement of goods within cities, with the Covid-19 pandemic acting as a catalyst for this transformation. This shift has influenced consumer behavior and altered freight movements in urban areas. Covid-19 accelerated digital transformation for many businesses that had not previously been heavily invested in that path. Travel bans, store closures, and global supply chain disruptions forced traditional and omnichannel retailers to adapt their strategies to reach consumers (Beckers et al., 2021). Pure online retailers with established web infrastructures were less affected compared to smaller retailers. A study in Spain by Acquila-Natale et al. (2022) highlighted that large clothing and apparel chains were better equipped with e-commerce options than small and medium-sized retailers. Consequently, retailers worldwide invested in e-commerce infrastructure and services. For instance, Belgium saw an increase from 40% to 70% in local retailers with e-commerce capabilities Beckers et al. (2021), and in Canada, the percentage of companies completing online orders rose from 25% in 2019 to 33% in 2021 (Gouvernement du Canada, 2023). Similarly, 71% of Canadian firms with web retail services offered transactional websites in 2021, up from 58% in 2019 (Gouvernement du Canada, 2022).

However, the shift to e-commerce introduced challenges such as a lack of staff expertise (Beckers et al., 2021; Gao et al., 2020), increased cybersecurity risks (X. Liu et al., 2022), and supply chain issues (Hossain et al., 2022). These challenges highlight the need for improved e-business management practices (Ünvan & Pampal, 2022). Moreover, the Covid-19 pandemic significantly impacted consumer behavior, the effects of which can be modeled using the react-cope-adapt framework developed by Kirk & Rifkin (2020). Initially, consumers reacted by stockpiling due to supply chain disruptions and perceived scarcity (Kirk & Rifkin, 2020; J. Sheth, 2020). In the coping phase, consumers sought alternative solutions to product scarcity, such as self-care products (Guthrie et al., 2021). Finally, in the adapting phase, purchasing patterns stabilized as consumers adjusted to the new normal (Guthrie et al., 2021; Kirk & Rifkin, 2020). Cruz-Cárdenas et al. (2021) categorize the factors influencing consumer behavior during Covid-19 into macro-environmental and psychological factors. Macro-environmental factors include fear of contracting the virus (Crosta et al., 2021; Grashuis et al., 2020; Nguyen et al., 2021; Sumarliah et al., 2022), social distancing (Kawasaki et al., 2022), and safety protocols (Kawasaki et al., 2022). Psychological factors, such as anxiety and fear, predicted necessity purchasing, while depression symptoms

predicted non-necessity purchasing (Crosta et al., 2021). Positive experiences during Covid-19 led to sustainable shopping practices, whereas negative experiences led to panic and revenge purchases.

The pandemic also triggered changes in freight movements within cities. Home delivery demand surged during the pandemic's first wave. In Canada, ordering groceries online became a prevalent activity (Bilodeau et al., 2021), and in the U.S., e-commerce sales increased by 31% between the first and second quarters of 2020 (Wang et al., 2021). Delivery drivers faced higher risks of contracting Covid-19 due to increased consumer contact (Harris & Kirkham, 2021; Tran et al., 2022). Studies in Toronto and Vietnam emphasized the need for better employer support and PPE for delivery drivers (Harris & Kirkham, 2021; Tran et al., 2022). In response, logistics providers innovated to meet the increased demand for home deliveries. Innovations included parcel lockers, mobile warehouses, and cargo bikes. Mobile warehouses helped prevent shortages in last-mile delivery (Srivatsa Srinivas & Marathe, 2021), and parcel lockers provided flexibility, reduced direct contact, and improved efficiency, also reducing fuel consumption by 74-87% per parcel (Milewski & Milewska, 2021; Sułkowski et al., 2022). Cargo bikes offer flexibility and efficiency in different settings, as demonstrated in a case study on Brussels, for which cargo bikes delivered twice as many clients as delivery vans (Kale Ai, 2023). The next section focuses on different studies with a specific emphasis on cargo bikes.

4.3.2 Review of cargo-bike studies

Research on cargo bikes for parcel deliveries has increased in recent years as this delivery mode represents an interesting alternative to delivery vans or trucks within city centres. Indeed, cargo bikes offer flexibility and reliability for proximity-based delivery networks (Schliwa et al., 2015). Studies on cargo bikes can be divided in three main consecutive phases.

Early day studies focus on the need to establish the potential and competitiveness of cargo bikes for freight transport. Gruber et al. (2014) identify that there is a potential for cargo bikes based on the data of six German cities. The same study also shows that the willingness to use cargo bikes is linked to personal messenger attributes, but also positive perception from the population and a dissatisfaction with the ecological footprint of traditional modes of transport for goods. Schliwa et al. (2015) highlight the role of local authorities in the successful implementation of cargo bikes initiatives for freight deliveries. The same article also identifies key factors that influence the

viability of cargo bikes operations, such as : weight, volume, distance, topography and presence of cycling infrastructures and parking facilities (Schliwa et al., 2015). Choubassi et al. (2016) explores the possibility of replacing last-mile mail deliveries with cargo bikes and shows that the economic feasibility is improved by the presence of biking infrastructures, local depots and high population density. To integrate the use of cargo bikes, new methods are developed. Tipagornwong & Figliozzi (2014) develop a cost model that is specifically tailored to cargo bikes and vans features. Anderluh et al. (2017) develop three distribution policies that consider cargo bikes and the corresponding solution algorithm. Findings for the case study based on Vienna show that costs can be cut by substituting vans by cargo bikes and that emissions are reduced in all three policies when cargo bikes are integrated (Anderluh et al., 2017).

Articles previously mentioned highlight the possibilities that cargo bikes offer, allowing the next generation of articles on cargo bikes focus on the integration, comparison, and evaluation of the presence of cargo bikes within vehicle fleets. Simulation based studies allow to integrate cargo bikes in different scenarios and to measure the impacts that they create. Using real data from the city of Antwerp, Arnold et al. (2018) analyse the cost-structure of different scenarios such as van deliveries, self-pick-up and cargo bike deliveries. The results of this case study show that the operational costs are reduced by 40 % when cargo bikes are used but delivery times are longer and the capacity of cargo bikes is problematic (Arnold et al., 2018). Using agent-based simulation, Fikar et al. (2018) show that consolidation practices at micro-hubs are beneficial for the competitiveness of cargo bikes. The same study also demonstrates that the availability of cargo bikes in sufficient numbers prevents increased delays in delivery times (Fikar et al., 2018b). Elbert & Friedrich (2020) use a hybrid agent-based simulation to carry out four delivery scenarios. Their results are coherent with those of Fikar et al. (2018) for Vienna (Austria) and Hofmann et al. (2018) for Grenoble (France) and Zhang et al. (2018) for Berlin (Germany). Indeed, consolidation amongst logistic providers and the integration of cargo bikes increase the economic viability of delivery operations for Frankfurt (Germany) (Elbert & Friedrich, 2020). Leite Nascimento et al. (2020) determine that the substitution of traditional modes of transport by cargo bikes is economically profitable in Brazil, due to the high density of population and lower costs of exploitation for cargo bikes. These results are coherent with Sheth et al. (2019), which proves that cargo bikes are competitive for higher density of residential units in a city. Other impacts that are measured when cargo bikes are integrated include environmental impacts (Conway et al., 2017a; Hofmann et al.,

2018; Koning & Conway, 2016; Melo & Baptista, 2017), road congestion (Koning & Conway, 2016), curbside utilisation and parking space (Conway et al., 2017a) and social acceptability (Gruber et al., 2014; Perboli & Rosano, 2019).

Based on these results, the impacts of integrating cargo bikes are better defined which, in turn, allows researchers to focus on improving their understanding of the demand and prerequisites for cargo bike deliveries. Prerequisites for cargo bikes include the presence of hubs for freight transit. Due to the weight, capacity and distance limitations of cargo bikes (Vasiutina et al., 2021), hubs must be strategically placed and must serve specific purposes. When it comes to hubs, several typologies currently exist, as synthetized by Katsela et al. (2022). Specifically, the study distinguishes between three operational models for micro-hubs (last-mile collaboration, shared infrastructure and private systems). The same authors also show that while an array of typologies allows for tailored solutions, it also might create confusion amongst stakeholders. Due to the importance of micro-hubs, their localisation is primordial to the success of cargo bikes. Rudolph et al. (2021) consider the type of road, the land-use as well as real demand data as the criteria to establish the location of the micro-hub. However, their work does not consider the input of different types of stakeholders and the locations are theoretical. In their localisation effort for Manhattan (United-States), Arrieta-Prieto et al. (2022) consider the societal cost when opening a micro-consolidation centre. However, their external cost only considers the pollution associated with the vehicles. In recent years, studies considering cargo bikes have started to focus more on the impacts of different environments on cargo bike operations. Dybdalen & Ryeng (2022) evaluates cargo bikes operations in wintertime in Norway, with the conclusion that cargo bikes are efficient provided that the bike can handle increased damage due to the weather and that cyclists be clothed for the weather. Giordano et al. (2022) investigates the impact of the weather and topology on the energy of cargo bike cyclists, allowing practioners to better evaluate the need for electric assistance and required adjustments for cyclists. Similarly, a case study based in Medellín (Colombia), integrates the mountainous terrain in their study design to better characterize the benefits of cargo bikes in the city (Gonzalez-Calderon et al., 2022). Dalla Chiara et al. (2023) establish how cargo cyclists use the infrastructure in which they operate and which type of infrastructure are needed for the future of cargo bikes, as advances in technology and design will improve the perceived usefulness and ease of use of cargo bikes in the future (Peppel et al., 2022).

4.4 Methodology

This section discusses the methodology chosen for this study. First, an overview of the data is given to explain the choice of a multilevel model. The second part of this section presents what a multilevel model is, followed by the model formulation and model implementation.

4.4.1 Overview of the data

The database on which this study is based was created from the beginning of the initiative and includes a total of 6,713 deliveries made by cargo bikes between March 13th and July 7th, 2020 (102 days) in Montreal, Quebec, Canada (Figure 4.1). Each record corresponds to a delivery and contains the origin of the delivery (i.e., store); the destination (delivery address); the date and times of calls for a delivery service by cargo bike, collection and delivery of goods; and the identification number for the delivery person. In total, 44 cargo bike delivery drivers were employed over 102 days of operation and 91 shops were part of the initiative. However, the dataset does not provide the volumes transported. The data was collected and provided by *Jalon Mtl* and *Coop Carbone*, two independent organisations based in Montreal.

The structure of the data at hand is nested. Each delivery done can be clustered by store (Figure 4.2). Each shop has a set of characteristics (detailed in section 4.4.2.2). As this study is performed in the specific time frame of the first wave of Covid-19, time variables can have an influence on the model chosen. Therefore, to account for the different levels of characteristics, a multilevel model is needed to identify the relevant variables influencing the delivery initiative.

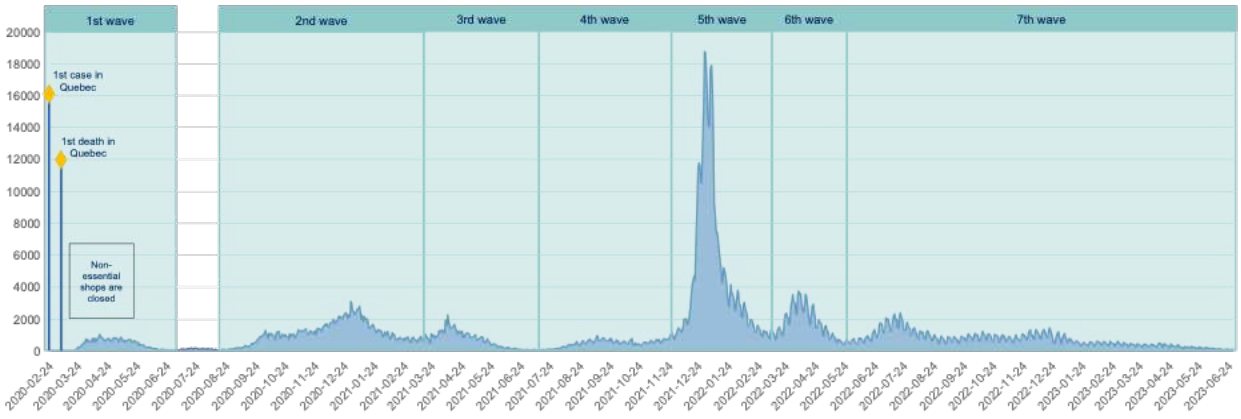


Figure 4.1 Waves of Covid-19 cases for Quebec (Canada)

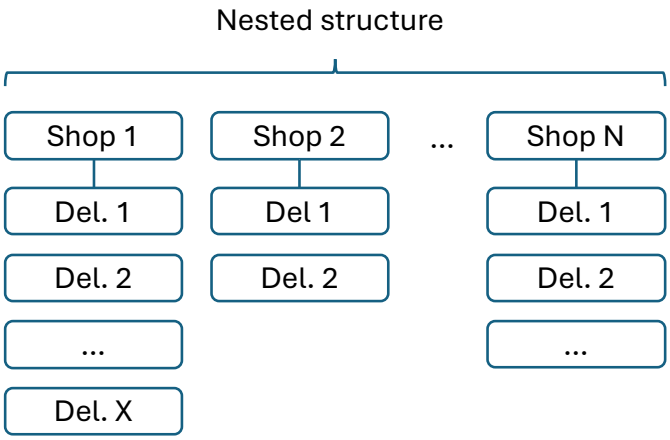


Figure 4.2 Nested structure of the data

4.4.2 Data preparation

To better characterize the time periods and the direct environment in which the delivery service by cargo bike performed (source A), additional data is provided and aggregated from different sources (Table 4.2). As the structure of the data is nested (Figure 4.2), all variables are added by level. The origin of added data is explained for each level. Source A refers to the collected data pertaining to the cargo bike delivery.

4.4.2.1 Level 1 additional variables

Level 1 is the lowest level and refers to the characteristics of each customer entry in the dataset. For this level, the median income, population density, average household size, average age, and the proportion of the population in three age categories are added for each delivery address. The data for these variables comes from the 2016 census done by the Governement of Canada (Government of Canada, 2017), called source B. For the variables pertaining to the census data, the number of observations corresponds to the number of dissemination areas in which one or more deliveries were made (n =1,000). Also pertaining to the first level, the number of active Covid-19 cases and a binomial indicator to signal the period of the lockdown are added. This binomial indicator comes from the Government of Quebec's official Covid website and database *Données COVID-19 au Québec* (2020), called source C. The average outside temperature and rainfalls are added from the national database on weather data (E. et C. climatique Canada, 2011) and called source D. The distance between the origin and destination is also computed for each entry using the Manhattan distance (source E). Source E refers to all calculations done by the authors.

4.4.2.2 Level 2 additional variables

Level 2 refers to the shop level. Four binomial indicators are added to characterize the participating businesses: (i) presence of a strong ecological mission, (ii) presence of a transactional website, (iii) presence of advertisements on social media, (iv) presence of the shop on the local shopping initiative's website. Each shop falls within one of these categories: fashion, food, home, leisure, and others. The shop's immediate environment is characterized by the number of other participating businesses and the number of bike-sharing stations and metro/bus stops all within an 800-meter radius. Finally, the number of times a shop has called for this service and the presence of advertising for the initiative are calculated from the data obtained by the business association (source E).

Table 4.2 Description of the additional variables

	Variable	Nb obs.	Level	Type	Min	Max	Mean	St. Dev.	Source
Number of deliveries	Number of deliveries per shop each week	6,713	IV	D	1	182.00	48.62	50.30	A
Calendar	Government mandate to close / open non-essential shops	102	1	B	0.00	1.00	0.81	0.39	C
Weather	Exterior temperature (°C)	102	1	C	2.80	25.89	10.56	6.47	D
	Rainfall (mm)	102	1	C	0.00	6.59	1.42	1.74	D
Accessibility	Number of bikesharing stations within a 800 m radius	91	2	D	2.00	19.00	7.49	12.24	E
	Number of public transport stops/stations (subway and bus) within an 800 m radius	91	2	D	0.00	26.00	15.21	7.68	E
	Distance between origin and destination (m)	6,713	1	C	65.35	10,256	1,510	1,013	E
Shop characteristics	General category of the shop	91	2	C	-	-	-	-	E
	Transactional website	91	2	B	0.00	1.00	0.90	0.31	E
	Shop belongs to the "local shopping initiative"	91	2	B	0.00	1.00	0.70	0.46	E
	Shop publicizes the delivery mode on social media	91	2	B	0.00	1.00	0.67	0.47	E

Table 4.3 Description of the additional variables

	Variable	Nb obs.	Level	Type	Min	Max	Mean	St. Dev.	Source
	The local business association publicizes the delivery mode to the general public	91	2	B	0.00	1.00	0.52	0.50	E
	Number of times a shop has used the service	91	2	D	1.00	68.00	40.13	17.85	E
	The shop has a strong ecological mission	91	2	B	0.00	1.00	0.22	0.41	E
	Number of other shops within a 800 m radius	91	2	D	1.00	18.00	8.54	4.49	E
Socio-demographic characteristics	Population density	1,000	1	D	91	4,669	633	295	B
	Average median after-tax income in private households	1,000	1	C	10,656	80,128	33,182	8,732	B
	Average age	1,000	1	C	23.40	79.00	39.19	4.43	B
	Proportion of people between 0 and 14 y.o. (%)	1,000	1	C	0.60	44.60	12.86	4.97	B
	Proportion of people between 15 and 64 y.o. (%)	1,000	1	C	12.30	96.00	75.97	8.24	B
	Proportion of people between 65 and 85 y.o. (%)	1,000	1	C	1.60	85.40	11.17	7.39	B
	Proportion of people older than 85 y.o. (%)	1,000	1	C	0.00	53.10	1.50	2.89	B
	Average household size	1,000	1	D	1.20	4.30	1.92	0.30	B
COVID-19	Number of active Covid-19 cases	102	1	D	80	990	732	246	C

Type : B = binary, C = continuous, D = discrete, IV = independent variable

4.4.3 The case for multilevel modelling

The use of multilevel models for transportation problems, whether in the case of passengers or freight is less common. However, the nested structure of transportation services should not be ignored (i.e., freight transportation services can be regrouped by carriers). Linear multilevel models are often used to determine important factors to explain or predict a behaviour. For example, Billot et al. (2009) studied the impact of rain on the driver's behaviour and Mercado & Páez (2009)

determined the variables that impact the distance travelled for the elderly. City logistics or last-mile delivery problems are particularly suited for multilevel analysis. Yuen et al. (2019) use structural equation modelling to determine the intention of use of parcel lockers for Chinese residents. The same authors have used hierarchical regression to understand the factors which influence the use of self-collect services in China (Yuen et al., 2018). In the case of our study, multilevel modelling is indicated because of the presence of a nested data structure. In order to obtain a better understanding of the factors that influence the success of the delivery initiative, we need to be able to consider the effects at the level of the delivery and at the level of the shop, as well as the time related effects created by the Covid-19 pandemic.

Multilevel modelling is a statistical method which is derived from the general structural equation framework (Mehta & Neale, 2005). Multilevel modelling is indicated when the data presents several hierarchical levels, with variables at each level and a research interest that spans over the different levels (J. Hox & Roberts, 2011). The motivations behind this type of modelling are (i) causal inference, (ii) prediction, and (iii) descriptive modelling (J. J. Hox et al., 2017). For the context of the present study and given the limited timeframe of the data collection, its use is thus mostly descriptive.

4.4.4 Model formulation

The equation for the linear multilevel model is adapted from Woltman et al. (2012). Equation (1) models the level 1 sub-model. This sub-model aims to represent the weekly changes in the number of deliveries for each shop (within the shop's variance). The level 2 sub-model, i.e., equation (2), aims to formulate the differences in the number of deliveries between each shop.

The dependent variable Y_{it} is the number of deliveries for a shop *i* in week *t*. T_t represents the time predictors associated to the number of weeks *t* elapsed since March 13, 2020 (beginning of the delivery service). X_{it} represents level-1 predictors that are used to assess the influence on the number of deliveries made over time. The direct environment of the shops is described by independent variables Z_i.

$$Y_{it} = \pi_{i0} + \pi_{i1}T_t + \pi_{i2}X_{it} + \varepsilon_{it} \text{ where } \pi_{i0} = \beta_{00} + \beta_{01}Z_i + r_{i0} \qquad (1)$$

And

$$\pi_{i1} = \beta_{10} + r_{1i}\,, \pi_{i2} = \beta_{20} + r_{2i} \qquad (2)$$

Level-1 errors are assumed to follow a normal distribution.

E(ε_{it}) = 0 and var(ε_{it}= σ^2)

Parameters:

π_{it} : level 1 regression coefficients

π_{i0} : intercept of the model, initial number of deliveries of shop i at time t = 0

π_{i1} : weekly change in the number of deliveries of business i over time (slope of the trajectory)

ε_{it} : error of level 1

β_{it} : level 2 regression coefficients

r_{it} : residuals of the model, for shop i at time t

4.4.5 Model implementation

All computations are executed with R, using the lme4 library (Bates et al., 2015) and verification was done using the nlme package (Pinheiro et al., 2020). A four-step implementation is followed, based on the work of Hox and al. (2017), synthesized at Table 4.4.

Step 1 consists of the intercept only model, also known as the null model. The intercept only model provides the AIC (Akaike information criterion) and BIC (Bayesian information criterion) of the model when no independent variables are added, thus acting as a baseline for the rest of the implementation. Each subsequent model should improve the AIC and BIC criteria by reducing them, therefore proving a better fit for the model overall. The null model is also useful to obtain the intra-class correlation (ICC). The intra-class correlation explains how much the total variation of a model lies between the clusters. This measure helps to validate the need for a multilevel model. Step 2 consists of adding the time variable predictors to the previous model. For this study, the time between the beginning of the service and week t is the time variable predictor considered. Adding time predictors helps to model that each individual considered (or in this case, delivery done) has a linear change trajectory due to the influence of time. Steps 3 and 4 are the repetition of step 2 with the incorporation of variables from the group level (level 2) and individual level (level 1). These variables are detailed in Table 4.2.

Table 4.4 Description of the implementation of the model

Step	Objective	Predictors considered	Outputs
Step 1	Validate the need for multilevel modelling	-	AIC / BIC / ICC
Step 2	Model that each delivery done has a linear change trajectory due to the influence of time	Time variable predictors	AIC / BIC
Step 3	Model the influence of level 2 predictors (group level)	Level 2 predictors (table 5)	AIC / BIC
Step 4	Model the influence of level 1 predictors (individual level)	Level 1 predictors (table 5)	AIC / BIC

4.4.6 Model assumption

There are three assumptions to satisfy a linear multilevel analysis: (i) normality, (ii) homogeneity of the variance, and (iii) residuals of the model are normally distributed.

To test the normality of the data at hand, the Shapiro-Wilk test was performed, and it yielded a p-value over 0.05, which confirms that the data has a normal distribution. It should be noted that the sample considered only contains sixteen weeks of data and that it cannot be used to assume that the normality condition will apply for a larger period. Performing Levene's test to assess the homogeneity of the variance yields a p-value inferior to 0.05, which means that the assumption of homoscedasticity is not entirely met.

For linear multilevel models, residuals of the model are assumed to be equally distributed. While we do not achieve perfect normality, the residuals appear to be equally distributed around 0 (Figure 4.3).

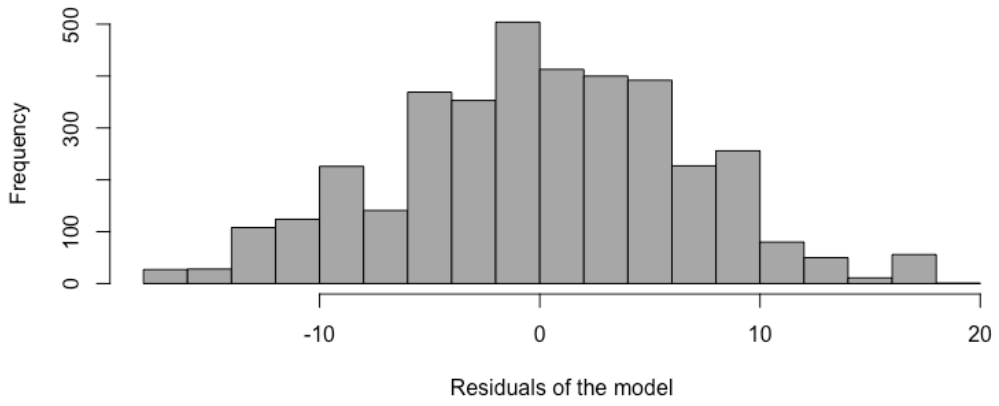


Figure 4.3 Histogram of the residuals of the model

The data at hand presents outliers. Many shops called for only one or two deliveries within the delivery initiative.

In this context, outliers are not deleted from the dataset as they represent the shops that did not adhere to the delivery service. The lack of participation in the service is as considered as the higher levels of participation.

4.5 Montreal case study

During the months of March to May 2020, the province of Quebec recorded on average between 500 and 700 new cases of Covid-19 per week over a population of 8.485 million inhabitants. Companies specialized in deliveries by cargo bikes voluntarily offered their services to shops in need of delivery alternatives, to quickly increase the delivery capacity for the city of Montreal. Cargo bike delivery services are not new in Montreal. Before the pandemic, they were used mostly by courier services in the downtown area as a business-to-business service (B2B). Nowadays they are used for both B2B and business-to-consumer (B2C) services for courier and parcel deliveries.

4.5.1 Understanding the bike delivery initiative

The bike delivery initiative studied in this paper was implemented a week after the announcement of the shutdown and lasted from March 27, 2020, to July 7, 2020. Companies specialized in deliveries by cargo bikes voluntarily offered their services to shops in need of delivery alternatives, to quickly increase the delivery capacity for the city of Montreal. Cargo bike delivery services are

not new in Montreal. Before the pandemic, they were used mostly by courier services in the downtown area as a business-to-business service (B2B). Nowadays they are used for both B2B and business-to-consumer (B2C) services for courier and parcel deliveries. This initiative is a joint effort from public and private actors to offer cargo bike deliveries for closed shops with competitive pricing. Conditions to be eligible for this service are: (i) the customers need to be within a five-kilometre range from the shop and (ii) products requiring specific storage, such as fresh food or frozen products, are not accepted. Consumers outside the delivery range are delivered by the traditional post. Costs were either assumed by the shop with a minimum amount purchased or transferred to the consumer.

The delivery service considered is on-demand. Shops are responsible for processing the order and call the delivery service when it is ready. A delivery person is then dispatched to the store and does the delivery either on the same day or the day after. For this initiative, the cargo bike delivery drivers are paid hourly wages, as opposed to a per delivery basis. Over the time periods of the initiative, the number of days worked by each delivery biker ranges from only one day to all of them. As the packages were mostly delivered on the same day, all delivery activity was done from 12 p.m. to 5 p.m. (on average), leaving the mornings for shops to prepare all orders. Orders received during the afternoon would either be picked up by a passing delivery biker or left for a following day delivery.

4.5.2 Understanding consumer's demand during the first wave of Covid-19

In total, 91 businesses participated in the initiative and are divided into categories summarized in Table 4.5. Bookshops, crafstore, game shops did the highest number of deliveries, followed closely by grocery shops, cafés and delicatessen. These shops were in high demand during the first wave of Covid-19 as people stayed mostly at home.

Table 4.5 Distribution of categories of participating businesses

Category	Description	Number of shops	Number of deliveries
Food	Grocery shops, cafés, delicatessen, etc.	35	2,100
Home	Home decor and furniture, etc.	8	947
Leisure	Board games, crafts, bookshops, etc.	21	2,306
Fashion	Clothes, shoes, sports equipment, etc.	11	913
Other	Miscellaneous (pharmacies, animal care, etc.)	16	387
Total		91	6,713

All businesses participating in the initiative are grouped by commercial street associations (Figure 4.4). There exists approximately one business association per neighbourhood for the city of Montreal. A business association regroups different types of shops to better defend their interest. Shops belonging to a business association benefit from pooled resources, such as marketing campaigns. In the context of our study, the business associations were involved in promoting and reaching shop owners to promote the bike delivery initiative. However, all groups do not have an equal distribution of business types within them.

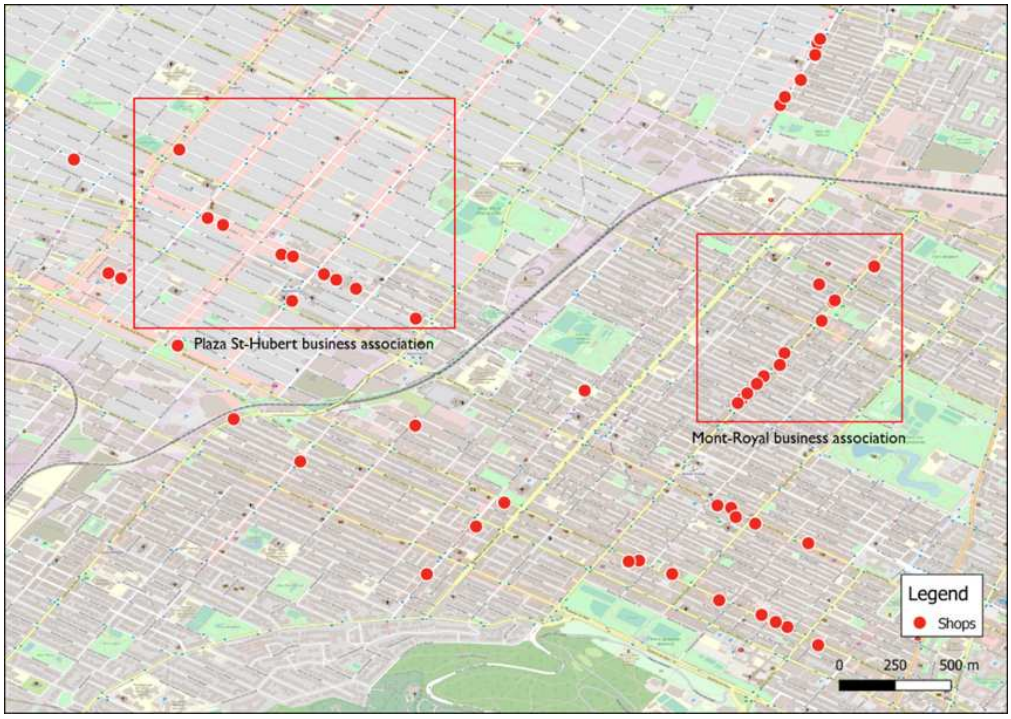


Figure 4.4 Sample of the participation business locations in Montreal

4.6 Results

This section presents the results obtained from the implementation of the different models. First, the evolution of demand is presented, based on the data collected. Section 4.6.2 focuses on the global results, including goodness of fit of the model and statistically important variables. Section 4.6.3 presents certain variables from the model in more detail.

4.6.1 Evolution of demand over time

Figure 4.5 and Figure 4.6 demonstrate that the demand for deliveries evolves with time. The number of deliveries done per week increased significantly. When Covid-19 numbers are added (Figure 4.6), it is possible to observe the link between consumer behaviour and the directives given by the government. Specifically, consumers are instructed to reduce their physical movements to prevent the propagation of Covid-19, which triggered the rise of home deliveries. The initial lockdown period was supposed to be two weeks (weeks 13 and 14 in figure 5) but this period was extended several times by the provincial government, from weeks 15 to 21 included. The diminution of Covid-19 cases allowed the government to reopen all businesses at the beginning of week 22, which triggered a strong reduction in the need for deliveries. After the reopening of

businesses, this cargo bike delivery initiative evolved to a larger initiative called “Envoi Montreal”. The “Envoi Montreal” initiative does not have the same goal, as it aims to regroup on a single platform all shipment possibilities for business owners, ranging from traditional modes of transportation to alternative ones such as cargo bikes. With “Envoi Montreal”, shop owners can compare the different alternatives mostly based on pricing. Therefore, as the evolution of the bike initiative completely changed, the focus of this study remains on the bike only initiative within the first wave of Covid-19. During the first month, people are mostly ordering food from grocery stores, delicatessen restaurants, and bookstores (the leisure activity category) (Figure 4.6). Then the demand for food stabilizes and the demand for leisure activities (books, crafts, games, etc.) and fashion continues to increase (Figure 4.6).

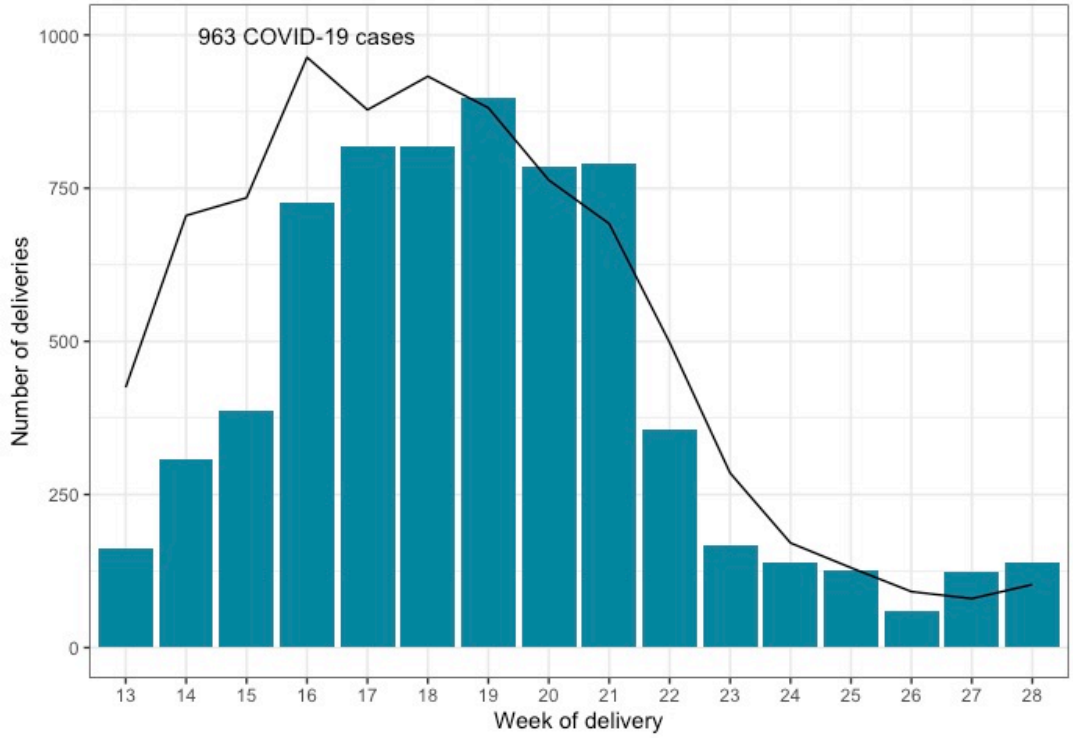


Figure 4.5 Evolution of the demand and Covid-19 cases

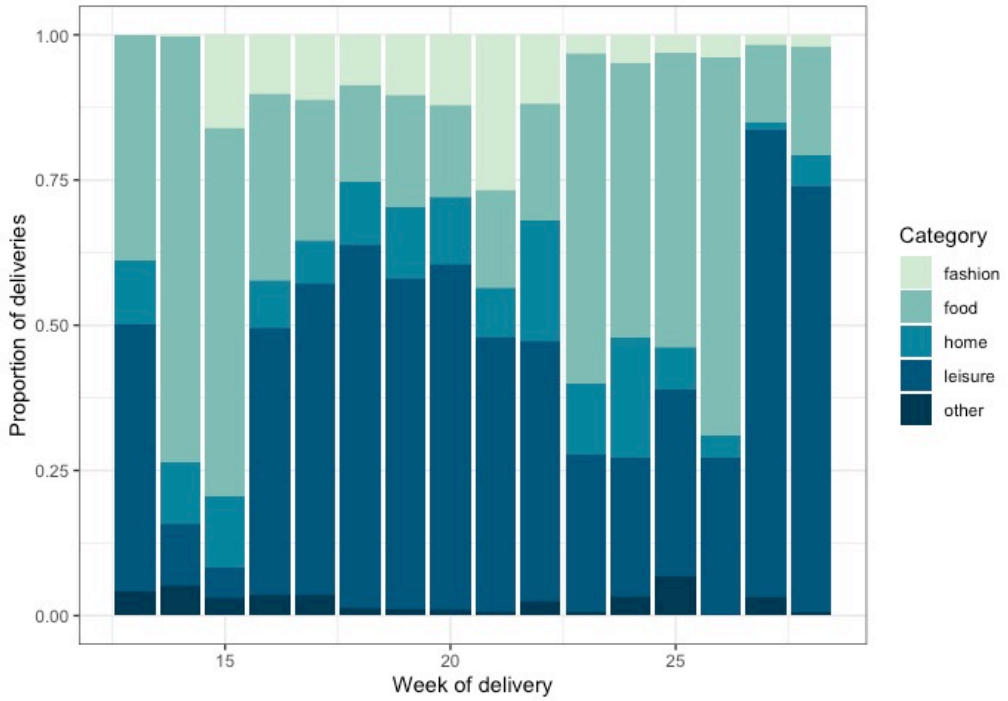


Figure 4.6 Evolution of the demand by category

4.6.2 Global results

Table 4.6 presents all the results obtained by implementing the successive models. The first four lines of Table 4.6 cover the goodness of fit of the models.

The intra-class correlation and the AIC and BIC indicators are used to evaluate the goodness of fit of the models. First, the intra-class correlation coefficient (ICC) from Model 0 shows the proportion of total variation in the model that exists between clusters. This high ICC value justifies the need to account for the hierarchical structure of the data in the delivery initiative. The ICC for Model 0 is 0.8976, indicating that 89.76% of the total variation is between shops, while 10.24% is within shops. This result indicates that a good comprehension of shop characteristics is important to understand the impacts on the generation of deliveries with cargo bikes.

The second element considered to build upon each model is the decreasing values of the AIC and BIC indicators. Overall, the goodness of fit indicators (AIC and conditional R2) are improved from model 0 to model 4. The AIC of the models decreases and the R2 improves between each iteration of the models. The conditional R2 of the final model (model 4) is 0.665 which means that 66.5 %

of the total variance is explained by all the variables considered. While it is not perfect, given the experimental aspect of the initiative and thus data gathered at hand, it is judged satisfactory.

Values presented under “fixed effects” in table 5 represent the intercept for each variable and its related statistical significance at the beginning of the service. Even though all variables mentioned in section 4.3 were tested in the different models, only the variables which are statistically significant are presented here. The results presented here are not the correlation coefficients between the variable and the number of deliveries done, but the starting number of deliveries linked to each variable.

Except for the variable “the initiative is publicized by the business association” and the variable “the shop has a strong ecological mission”, other results are centred around zero, which means that their relative influence at the beginning of the delivery service (week 13) is moderated. This could be explained by the fact that the data is concentrated on a short period of time.

Table 4.6 Results of the different models

	Model 0		Model 1		Model 2		Model 3		Model 4	
AIC	63639.39		60163.54		59854.49		59815.49		59685.77	
BIC	63659.87		60204.5		59902.19		59917.88		59788.17	
Marginal R^2			01.41 %		04.79 %		28.02 %		25.14 %	
Conditional R^2			59.21 %		62.21 %		67.57 %		66.76 %	
Fixed effects										
Intercept	1,41E+01	***	6,47E+01	***	-3,21E+01	**	-3,41E+01	*	-5,60E+01	***
Time elapsed			-1,12E+00	**	9,98E-01	.	9,69E-01	.	2,15E+00	***
Time predictor										
Covid-19 (covid_cases)					3,45E-02	***	3,45E-02	***	4,81E-02	***
Level 2 predictor										

Table 4.7 Results of the different models

	Model 0	Model 1	Model 2	Model 3		Model 4	
Initiative is publicized by the local association (ad_del)				2,75E+01	**	2,99E+01	***
Ecological mission (eco)				-1,27E+01	.	-1,40E+01	*
Level 1 predictor							
Median income after-tax at destination (income_del)						-8,00E-05	*
Rainfall (rainfall)						2,37E+00	***
Average age in household (ave_age)						5,46E-01	.
Proportion of people between 15 and 64 y.o. (cat_age_1564)						-2,98E-01	***
Proportion of people between 65 and 85 y.o. (cat_age_6585)						-1,94E+00	***

Significance levels : 0 ‘***’ | 0.001 ‘**’ | 0.05 ‘*’ | 0,1 ‘.’ | 1 ‘ ’

4.6.3 Interpretation of significant variables

To better interpret the model, a projection of the number of deliveries is done considering three levels of Covid-19 cases per week for the province of Quebec and the variable considered, starting from the beginning of the delivery initiative. The three levels Covid-19 considered are 485 Covid-19 active cases per week, 732 active cases and 978 active cases. These three levels were obtained by clustering the number of active cases over the time period of 16 weeks. The projection is done on a set of variables which are significant such as: ecological mission, household size, average age in household, rain and advertisement done for the delivery initiative.

Shops with a strong ecological mission (eco =1), such as zero-waste grocery shops, tend to generate fewer deliveries than other shops (Figure 4.7). When considering the lowest level of daily Covid-19 cases, shops without a strong ecological mission generate on average 154 % more deliveries than shops with a strong ecological mission on the considered period. For the middle and highest numbers of daily Covid-19 cases, shops without a strong ecological mission generate respectively 50.44 % and 33.45 % more deliveries than shops with a strong ecological mission on the considered period. With higher Covid-19 active cases, the number of deliveries done by the delivery initiative increases, as the convenience of home deliveries outweighs potential personal beliefs about home deliveries.

This may be explained by the fact that consumers interested in shopping in this type of establishment are more conscious about the environmental and social costs of deliveries and try to avoid them. When customers are informed about the social and environmental costs of a delivery, they tend to prioritize the most eco-friendly solution or avoid the deliveries altogether (Buldeo Rai et al., 2021; Ignat & Chankov, 2020).

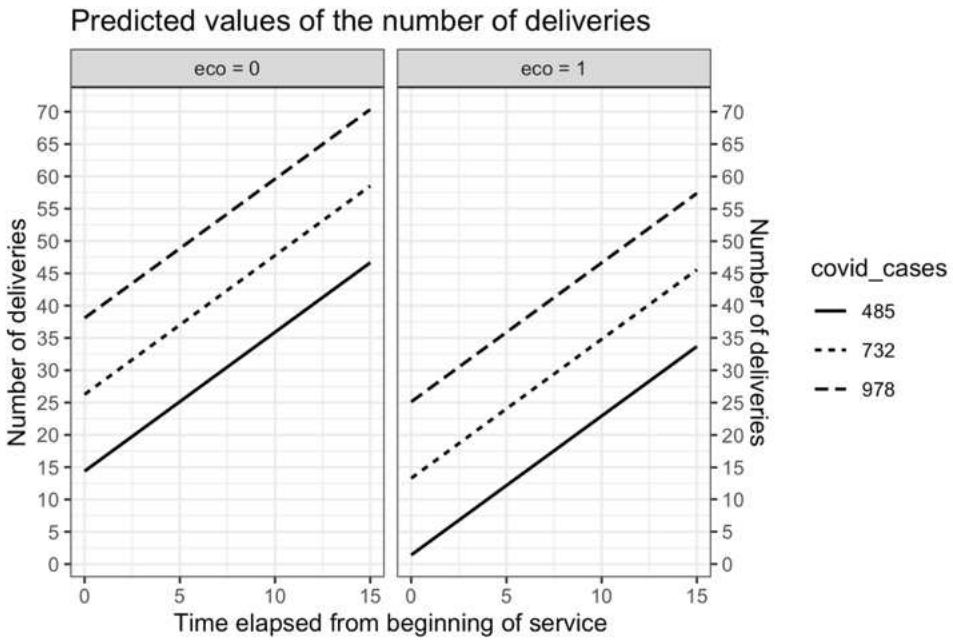


Figure 4.7 Number of deliveries considering the ecological mission of a shop

The household size variable indicates that smaller households tend to generate more deliveries within the system. When comparing the predicted values for different sizes of households (single person, couple, and small family, for example), households with only one person generate on average about 26.14% more deliveries than a four-person household (Figure 4.8) when the number of Covid-19 cases is low, 16.33 % and 12.08 % when Covid-19 cases are respectively moderate and high. The rising number of Covid-19 cases yielded more deliveries made by all household sizes. Car ownership could explain these results as larger households are more likely to possess their personal vehicle when compared to a single-person household (Cheng et al., 2021). Furthermore, the type of participating shops in this initiative might appeal less to larger households.

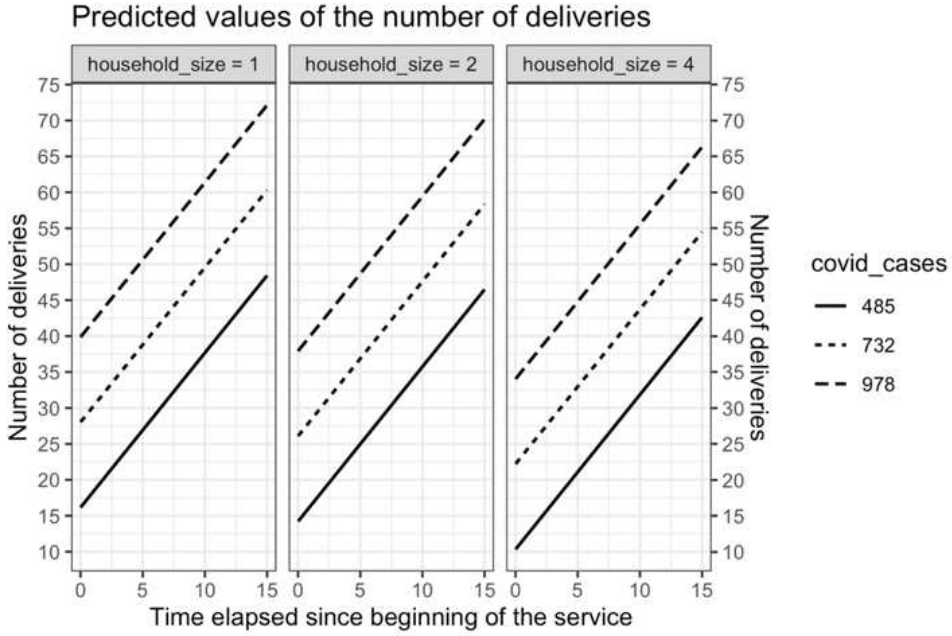


Figure 4.8 Number of deliveries considering household size

However, when the average age in the household increases, the number of deliveries also increases by 31.96 % when Covid-19 cases are lower, 23.36 %, and 18.59 % when Covid-19 cases are respectively moderate and higher (Figure 4.9). Again, the rising number of Covid-19 cases influences the proportion of consumers who benefited from the cargo bike delivery system. These findings are coherent with the typology of shops present in the study, which tend to be specialized and independent shops. Another hypothesis is that older consumers have a larger purchasing power than younger consumers.

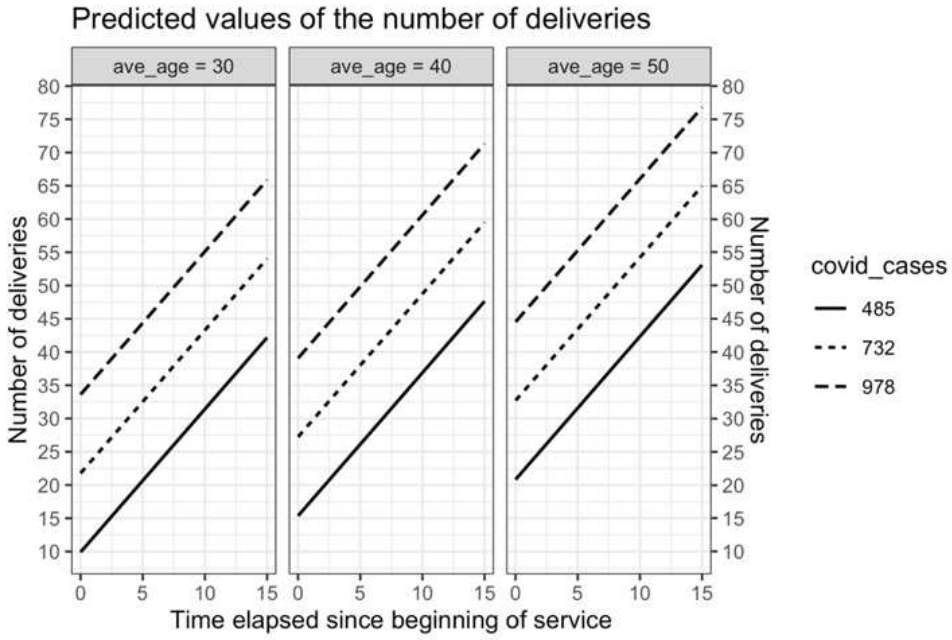


Figure 4.9 Number of deliveries considering the average age (in years)

A larger purchasing power is often correlated to a higher income for households. In this model, there are close to no differences between the different incomes perceived by consumers. By design, all deliveries happened in a very close radius (about 3 kilometres). Therefore, the differences between the household income tend to be small which, in turn, limited the overall impact of considering the household income in our model. Wang & Zhou, (2015) prove that an increase in 10,000 US$ only results in a marginal increase in the number of deliveries. Therefore, the income variable should be better examined in the future.

The possession of a credit card and the use of the internet are two variables that influence the number of deliveries generated. Older consumers are less likely to do web purchases than younger consumers, which is then reflected in the number of deliveries generated. In this model, the proportion of people aged between 65 and 85 years old in the census area of delivery shows that when the proportion of people within this age category increases, the number of deliveries performed significantly decreases (Figure 4.10).



Figure 4.10 Number of deliveries considering the proportion of 65-85 y.o. in the census area of delivery

Outside of the demographic variables, the amount of rain impacts the number of deliveries performed. As almost 63 % of the deliveries were performed on the same day as the order, one can deduce that when heavily raining, consumers generated more deliveries. On average, days without rain generated 36.45 % fewer deliveries than heavy rain (rain = 6 mm) for a low number of Covid-19 cases, 27.62 % and 22.31 % fewer deliveries for moderate and high numbers of Covid-19 cases respectively (Figure 4.11). On average, between the months of March to June, Quebec receives around 110 mm of rain per month. Therefore, the population might be more tempted by home deliveries during this period.

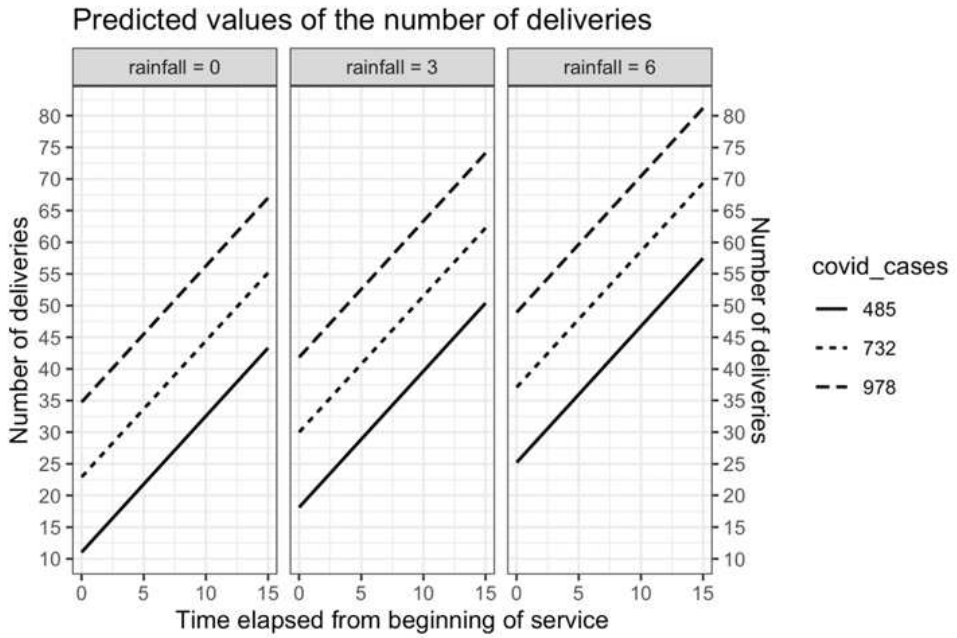


Figure 4.11 Number of deliveries considering rainfall (in mm)

Finally, the variable with the most impact on the delivery demand is the advertising done specifically for the cargo bike delivery initiative. Each participating shop is affiliated with one business association, whose actions are independent from one another.

Therefore, some of the business associations decided to invest in advertising to promote the type of delivery (ad_del = 1). Whether it is advertising on social media, banners, or stickers distributed, shops that benefited from this advertising generate significantly more deliveries than those that did not. On average, when Covid-19 cases are low, shops benefiting from the advertising generate 110 % more deliveries and 74.90 % to 57.15 % more for moderate and high numbers of Covid-19 cases (Figure 4.12). The very high increase for the low number of Covid-19 cases can be explained by the fact that the advertising campaign was proactive and in place at the very beginning of the restrictions, hence procuring participating businesses with a competitive strategy for deliveries when all other delivery methods were slower.

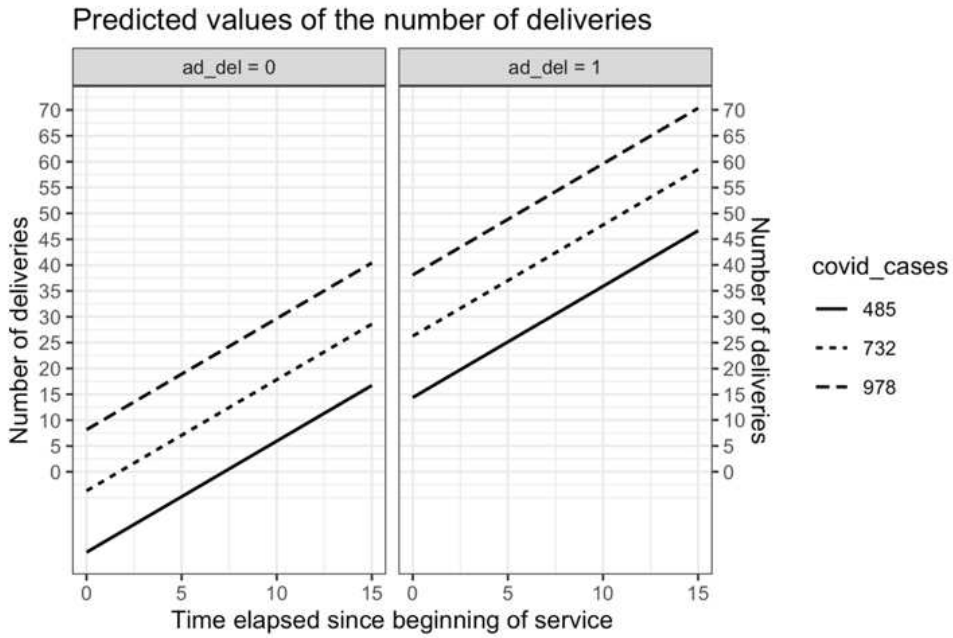


Figure 4.12 Number of deliveries considering the advertising campaign

4.7 Conclusion, limitations and future work

This study proposes a multilevel linear model to better reflect the evolution of the factors influencing the delivery system in time and the diversity of shops considered in the system. Socio-demographic factors, such as household size and average age within household are important to consider. Advertisement about delivery and the mission of a shop should also be considered properly when designing a delivery initiative.

We consider the approach of a multi-level model useful for both policymakers and delivery actors to understand which variables to factor when implementing a cargo bike delivery system in the future. Without the multilevel modelling, shop's characteristics would not be considered, and this could lead to a stronger bias when it comes to planning a bike delivery system. In the case of the first wave of Covid-19 context, shops that were strongly advertising for the bike delivery initiative performed much better than passive businesses. This paper also presents the following effects of Covid-19 on urban delivery systems and aims at providing a deeper understanding of the rapid changes that occurred. This study also acts as a proof of concept for the city of Montreal to guide future developments for the industry. As pointed out by Narayanan and Antoniou (2022a), a logistics system based only on cargo bikes may not always be realistic. However, this study shows that the use of cargo bikes on smaller perimeters and as a temporary solution proves to be useful

and doable, when adequately supported by policies and support campaigns. In this context, the Covid-19 pandemic allowed a better penetration of cargo bikes within the ecosystem.

This initiative was the result of a close collaboration between the public and private sectors. This collaboration was made possible by the fact that the city of Montreal was already involved since 2019 in cycle logistics. Furthermore, two independent third parties (Coop Carbone and Jalon Mtl) played a significant role in the success of the collaboration, as both organisations had strong relations with both the municipal authorities and the cargo bike community, making it possible to connect all parties efficiently. Moreover, the two third-party organisations acted as neutral actors, collecting relevant data as soon as the initiative was launched. The urgency and the unprecedented context may also have contributed to the speed of the initiative's implementation. From the perspective of this initiative, it operated as a trial-and-error process, during which each iteration of the project brought slight modifications. Once again, the particular context of the initiative enabled the project to be conducted.

This study does not consider several factors which could have significant impacts on the number of deliveries made, such as the presence of a competing delivery system (shops delivering to their customers by themselves or via traditional methods only), or the notion of cannibalism among businesses. The presence of a high number of businesses that are part of the delivery initiative and belong to the same category could lead to fewer deliveries being made, as consumers divide their choices amongst different shops. Furthermore, all the data considered in this study only covers the first wave of the pandemic in Montreal, whereas several subsequent waves have already taken place with different restrictions imposed by governments. Since the beginning of the initiative, shops and carriers have been able to learn from previous operational results and improve the business model. The sample of data only covers participating businesses from main commercial streets. Moreover, the data gathered for this initiative does not include consolidation amongst cargo bike delivery drivers or trips. Consolidating the parcels would lead to a better operational system, which could have an impact on the key variables studied here.

Further research is required to gain a more comprehensive understanding of the evolution of demand as the initiative underwent a transformation into a new project, designated as "Envoi Montréal", which regroups different shipping options on the same platform. Subsequent to this

pilot project, it would be advantageous to examine the long-term consequences of consumer behaviour shifts on cargo bike delivery systems.

CHAPITRE 5 ARTICLE 2 : « URBAN INFRASTRUCTURE AND RIDER PREFERENCES IN CARGO BIKE DELIVERIES: INSIGHTS FROM MONTREAL »

Cet article est soumis dans le “Journal of Cycling and Micromobility Research” (le 07 avril 2025). Une grande partie de la codification des vidéos a été réalisée par Meriem Ines Aoufi lors de son stage à l’été 2023.

URBAN INFRASTRUCTURE AND RIDER PREFERENCES IN CARGO BIKE DELIVERIES: INSIGHTS FROM MONTREAL

Suzanne Pirie, Martin Trépanier, Walter Rei

5.1 Abstract

With the increasing demand for sustainable urban logistics solutions, cargo bikes have emerged as an efficient alternative to traditional motorized delivery vehicles, particularly in dense urban areas like Montreal. While research has largely focused on their efficiency and environmental benefits, operational challenges and infrastructure interactions remain underexplored. This study aims to bridge this gap by examining cargo bike delivery operations and characterizing how riders interact with urban infrastructure. Using a mixed-methods approach, we integrate surveys, interviews, GPS tracking, and video observations to analyze delivery patterns, infrastructure usage, and seasonal variations. Our findings reveal key operational constraints, including cargo handling complexities, infrastructure limitations, and parking challenges. Moreover, we highlight how winter conditions significantly impact cargo bike efficiency, influencing route selection, road-sharing behavior, and parking strategies. The study contributes to urban logistics research by providing empirical evidence on cargo bike operations, informing policymakers, urban planners, and logistics providers on best practices for optimizing infrastructure and delivery networks. By addressing these challenges, cargo bikes can become a viable long-term solution for sustainable urban freight transport.

Key-words : cargo bike, urban logistics, transport infrastructure, driving behavior

5.2 Introduction

Urban logistics is undergoing a significant transformation as cities seek sustainable alternatives to traditional delivery methods. In the aftermath of the COVID-19 pandemic, the rapid growth of e-commerce and the reorganization of supply chains have intensified pressure on urban delivery systems, accelerating the need for flexible and sustainable last-mile solutions. In Montreal, around 900,000 deliveries are performed each day (Meloche et al., 2025), and most of these deliveries are still performed by traditional modes of transport. However, cargo bikes have emerged as a promising solution for last-mile deliveries, offering an environmentally friendly and space-efficient alternative to motorized delivery vehicles (Narayanan & Antoniou, 2022a). By reducing congestion, lowering emissions, and improving accessibility in dense urban areas, cargo bikes contribute to more sustainable urban mobility. Cargo bike used for deliveries represent a growing trend within the scientific literature in the field of urban logistics. Research has primarily focused on their efficiency compared to vans and trucks or on their environmental benefits, often overlooking the operational challenges that cargo bike riders face throughout the delivery process. The preferences of the main parties involved, such as the cargo riders and their interaction with urban infrastructure remains insufficiently explored, despite its critical role in shaping delivery efficiency, safety and sustainability.

This paper aims to address these gaps by examining the often-overlooked aspects of cargo bike delivery operations and characterizing the patterns of infrastructure use among cargo bike riders. Therefore, the two main research questions for this article are:

- What are the key operational challenges in the cargo bike delivery process that remain overlooked in existing urban logistics research?
- How do cargo bike riders interact with urban cycling infrastructure, and what patterns emerge in their usage across different environments and seasons?

To answer these questions, this study adopts a mixed-methods approach, combining surveys, interviews, GPS tracking, and video observations to provide a comprehensive understanding of cargo bike delivery dynamics in Montreal. By analyzing rider behavior, infrastructure use, and seasonal variations, this study highlights the logistical, infrastructural, and environmental factors that influence cargo bike deliveries. The findings offer new insights into the constraints and opportunities within this growing sector, informing policy recommendations for urban planners,

logistics providers, and city officials aiming to enhance the viability of cargo bike deliveries. Ultimately, this study contributes to the broader discussion on sustainable urban freight by providing an in-depth analysis of cargo bike operations and their interaction with cycling infrastructure. By bridging the gap between research and practice, it seeks to support the integration of cargo bikes into urban logistics frameworks, ensuring their long-term success as a viable alternative to conventional delivery vehicles.

The rest of the article is organized as follows. Section 5.3 covers the scientific literature linked with understudied steps within the delivery process with cargo bikes. The different data sources and data treatment methods are presented in Section 5.4. Section 5.5 details the results of our study highlighting operational challenges and infrastructure use patterns. Section 5.6 discusses the broader implications of the findings for urban logistics and infrastructure planning and concludes the paper by summarizing the key insights and proposing avenues for future research.

5.3 Literature review

The literature on cargo bike logistics has grown in recent years, yet significant gaps remain in our understanding of their operational constraints and optimization strategies. Traditional research on urban logistics has primarily focused on trucks and vans, while studies on cargo bikes have often been limited to high-level assessments of their environmental benefits and efficiency. However, cargo bike deliveries encompass multiple intermediate steps—each presenting distinct challenges that warrant deeper examination. This literature review dissects these steps, including loading, biking, parking, and delivering, to identify critical research gaps. By drawing comparisons with truck and container logistics, as well as existing studies on cyclist behavior, this section aims to highlight the unique characteristics of cargo bike operations that remain underexplored. Understanding these gaps is essential for improving cargo bike logistics, developing supportive infrastructure, and optimizing urban delivery networks.

5.3.1 Loading the cargo bike

When loading a cargo bike, whether assisted by electrical power or not, it is crucial to consider various parameters such as dimensions, configurations and weight capacity. Additionally, factors like itinerary order, weight distribution, and battery capacity play significant roles. While these

parameters are often discussed in literature related to loading trucks and containers, there is a notable lack of concrete examples specifically addressing cargo bike loading.

Loading operations for trucks, containers, and cargo bikes are governed by several constraints. The Single Container Loading Problem (SCLP) delineates key constraints for efficient container loading, including prioritizing customer orders and placing the last loads towards the back of the trailer or container (Nascimento et al., 2021). Safety is another crucial consideration, especially when handling palletized loads on trucks and containers. Cargo bikes, which typically transport itemized loads, pose unique risks such as musculoskeletal pains and injuries for the rider. Despite this, there is a lack of studies focusing on cargo bike loading safety. However, a study by Ahmad et al. (2023) conducted in Eastern Asia on the food delivery by bike industry sheds light on the prevalence of upper and lower back pains in this sector.

Load balancing and cargo stability are particularly important for truck operations, container handling and cargo bikes. Load balancing entails adhering to weight capacity and distribution for safety and efficiency. In the case of trucks and cargo bikes, the weight capacity is determined by the load-bearing capacity of the axles (Martínez et al., 2015), whereas for containers it is determined by the crane's capacity. Notably, cargo bikes require better load control and stabilization. as identified and addressed by Pai et al. (2021). However, there is a gap in research concerning the relative weight of the cargo rider compared to the payload and the total weight of the bike, particularly regarding its impacts on batteries, axle strain and energy expenditure versus input. This contrasts with trucks, where the weight of the driver compared to the total weight of the truck is negligible.

Stacking and positioning constraints are crucial for maintaining the integrity of the delivered items. Positioning constraints encompass factors like item orientation (Martínez et al., 2015). Naumov & Pawluś (2021) employ 3D modeling constraints to optimize cargo bike packing in their simulation, emphasizing the need for a Last-In-First-Out strategy to prevent disturbing other boxes during delivery. Given that cargo bike riders handle itemized parcels, the stacking and positioning process can be iterative, involving multiple repetitions of unloading and reloading the box.

With the increasing market penetration of electric trucks and cargo bikes, battery optimization during loading activities becomes particularly important. For trucks, charging infrastructure plays a critical role (refer to Al-Hanahi et al. (2021) for a detailed literature review on the subject).

Conversely, for cargo bikes, battery swapping is more common due to battery size limitations. Aiello et al. (2021) conducted a study testing various battery sizes in relation to payload using a multi-objective approach, highlighting the importance of selecting the right battery size and configuration for the delivery system's needs. Fontaine (2022) considers the weight of both the cyclist and the cargo in determining the power consumption of an electric cargo bike, while Giordano et al. (2022) assess the relationship between payload and speed for cargo bikes without considering the weight of the rider.

This comparison aims to highlight the gaps in the literature regarding cargo bike loading. While cargo bikes are subject to similar constraints as truck and container loading, they operate on a much smaller scale and with less maneuverability. Future studies could focus on comparing different configurations of cargo bikes. These configurations include variations in the types of boxes used for goods storage during delivery, as well as different axle configurations. One of the unique aspects of cargo bike loading is the need to consider the battery capacity to manage the entire delivery route. Given the limited space available for cargo bike loading, there is an increased necessity to understand the degree of over-packaging compared to the volume and weight of items. This understanding is crucial for minimizing empty space within cargo bike boxes and optimizing delivery efficiency.

5.3.2 Biking to destination

This subsection examines the various parameters influencing cyclist behavior on the road and assesses their applicability to cargo bike riders. The study of cyclist behavior has become an increasingly prominent topic in the scientific literature. Useche et al. (2018) develop a questionnaire to measure cyclists' road behaviors, demonstrating that behavior varies based on gender, age, and cycling experience. Their findings on gender and age align with those of O'Hern et al. (2020), who further establish a link between personality traits—such as extroversion—and cycling behavior. Billot-Grasset et al. (2016) identify multiple factors contributing to cycling accidents, including behavioral aspects such as speed and alcohol consumption, as well as external factors such as adverse weather conditions, nighttime cycling, intersections, and infrastructure quality.

For commercial cargo bike riders, infrastructure and external factors also play a crucial role. Dalla Chiara et al. (2023) analyze infrastructure use by commercial cargo bike riders in Seattle (USA),

revealing that riders spend 37% of their total travel time on sidewalks while only 5% occurs on designated bike lanes. Their findings underscore the impact of inadequate infrastructure for both cycling and parking the cargo bikes. The relationship between cycling behavior and broader mobility culture is well-documented. Clark et al. (2019) examine infrastructure preferences in cities where cycling culture is emerging and conclude that cyclists favor separated bicycle infrastructure. In established cycling cities such as Copenhagen and Stockholm, Haustein et al. (2020) find that cycling levels are primarily influenced by the overarching mobility culture, shaped by infrastructure, policies and social norms.

Weather conditions and topography also significantly impact cargo bike riders. Giordano et al. (2022) study energy expenditure in various European cities, concluding that hilliness and wind speed strongly affect riders' energy use. However, this study does not address how cargo bike riders adapt their road behavior in response to these environmental factors. Hong et al. (2020) highlight the need for investment in cycling infrastructure to mitigate the effects of adverse weather conditions and enhance cyclists' resilience, based on observations in Glasgow (Scotland). In regions experiencing harsh winter conditions, such as Norway and Canada, further adaptations are necessary. Dybdalen & Ryeng (2021) investigate the effects of winter weather on cargo bike riders and find that riders reduce their speed and travel distance during winter cycling. Interviewed riders also report that snow and slush impair maneuverability. Despite these insights, further research is required to fully understand how extreme weather conditions influence cargo bike riders' behavior and what additional infrastructure may be needed to support their mobility.

5.3.3 Parking the cargo bike

Once at the destination, the cargo bike rider must temporarily leave the bike to complete deliveries. Unlike regular bikes or personal cargo bikes, commercial cargo bikes have distinct parking needs that stem from their operational requirements, frequency of stops, and the need to secure both the bike and the transported goods.

Studies indicate that the time spent parking for deliveries is relatively short. Dalla Chiara et al. (2023) found that, on average, cargo bikes used for delivery services in Seattle (USA) park for approximately four minutes per stop. In New York City, Conway et al. (2017) observed that 68% of deliveries by one operator were completed in under ten minutes, while 94% were completed within twenty minutes. In the same study, for another operator, the average delivery time ranged

from 9.2 minutes to 19.4 minutes during peak hours. In contrast, personal bicycles tend to be parked for extended periods, such as at workplaces or residences, as highlighted by Heinen & Buehler (2019).

Security is a major concern for cyclists when parking their bikes, as they prefer facilities that protect against theft and degradation (Yuan et al.. 2017). A study conducted in Montreal by Van Lierop et al. (2015) emphasizes that the location and type of parking facility significantly impact security. For commercial cargo bikes, this concern extends beyond the bike itself to include the transported goods. The level of security required depends on the bike's configuration, particularly if it includes detachable or mounted trailers. To date, no study specifically examines the security of commercial cargo bikes during parking. However, one could argue that the short duration of stops may act as a deterrent to theft.

Parking availability for delivery vehicles is often limited, especially in dense urban areas, leading to behaviors such as queuing, double parking, and stopping in unauthorized locations (Conway et al.. 2017; Gonzalez-Calderon et al.. 2022). This can result in increased fines, as observed in studies on commercial vehicle parking (Holguín-Veras et al.. 2011).Cargo bikes benefit from their compact size compared to vans, allowing for more flexible parking options. However, research on cargo bike parking strategies remains limited. Dalla Chiara et al. (2023) categorize parking behaviors into sidewalk parking, curb parking, and off-street parking. Their study found that 79.9% of the time, cargo riders in Seattle chose to park on sidewalks, followed by curb parking (<20%) and off-street parking (<3%). Additional distinctions were made regarding curb parking, including passenger load zones, bus lanes, commercial vehicle load zones, paid parking spots, and no-parking zones. Tipagornwong & Figliozzi (2014) accounted for parking difficulties in their model for diesel vans but assumed that freight tricycles could park anywhere with zero search distance. Conway et al. (2017) also noted that cargo bike operators can complete deliveries more efficiently since they are generally unaffected by parking regulations that apply to vans and trucks.

Cargo bikes, whether used for freight transport or personal purposes, require designated parking solutions tailored to their specific dimensions and operational needs. Keler et al. (2021) identified parking challenges as a deterrent to personal cargo bike use. However, research on parking strategies for commercial cargo bikes is still lacking. Future studies should focus on identifying

common parking patterns, the decision-making process of riders, and the infrastructure requirements necessary to support commercial cargo bike operations.

5.3.4 Walking with the parcel(s) to the destination

Walking the goods to the final delivery point is often an underestimated aspect of the cargo bike delivery process. Unlike truck drivers, who frequently use two-wheel hand trucks to facilitate parcel handling, cargo bike riders must carry parcels manually, increasing their risk of work-related musculoskeletal disorders (WSMD), particularly lower back pain. Several studies have established a strong link between lower back pain and manual material handling. Awang Lukman et al. (2019) found that among 110 commercial delivery drivers, the prevalence of lower back pain exceeded 65%, with 45% of those who frequently handled goods being at an even higher risk. These findings align with those of Bovenzi et al. (2006). A more comprehensive literature review on this topic is available in Sekkay et al. (2018).

The distance cargo bike riders must walk to complete a delivery varies. A study conducted in Seattle (USA) using GPS and camera observations by Dalla Chiara et al. (2023) determined that the average Euclidean distance between a parked cargo bike and the final delivery location is 32 meters. One of the primary advantages of cargo bikes, as noted by Koning & Conway. (2016), is their ability to park closer to the delivery destination compared to trucks or vans. However, larger cargo bikes often require additional parking space, making direct access to delivery points more challenging (Rudolph & Gruber, 2017). As a result, walking with parcels remains an unavoidable part of cargo bike deliveries.

Despite its significance, the physical effort required to walk parcels to their final destination remains underexplored in existing research. Further studies are needed to assess the prevalence and severity of physical strain associated with this activity, particularly when combined with the physical demands of riding. Additionally, research should consider the challenges posed by multi-story buildings in lower-density areas where elevators are not always available, as climbing stairs with heavy parcels may exacerbate physical strain for cargo bike riders. Addressing these gaps is crucial for developing ergonomic solutions and optimizing cargo bike delivery efficiency.

5.3.5 Handing out the parcel(s) at destination

Client interactions are an integral but often overlooked part of delivery operations. While no studies focus specifically on cargo bike couriers, research on gig economy workers suggests that customer interactions can significantly impact delivery personnel. Negative interactions, including customer aggression, have been linked to stress and unsafe driving behaviors (Montoro et al.. 2018; Useche et al.. 2018). Algorithmic management used by gig economy platforms can also influence how client-oriented delivery workers are, either positively or negatively (Wu et al.. 2023). In contrast, positive customer interactions can enhance job satisfaction, as shown in initiatives like the French postal service's home visits and the Meals on Wheels program in the U.S. Thomas et al. (2020).

With online sales projected to account for 24% of global retail (Forbes Advisor, 2024), demand for delivery services is increasing. Environmentally conscious consumers are also showing a preference for greener delivery methods. Studies indicate that when provided with ecological impact information, customers are more likely to choose sustainable options. This trend presents an opportunity for cargo bike deliveries to gain traction while fostering positive customer interactions, improving workforce retention and satisfaction.

Failed deliveries are a well-known issue in urban logistics, typically mitigated with solutions tailored for vans and trucks. However, research on home delivery failures specific to cargo bikes remains scarce. The attended home delivery (AHD) problem, where customers must be present to receive parcels, poses challenges such as scheduling uncertainty and environmental impacts from repeated delivery attempts (Agatz et al., 2008; Manerba et al., 2018).

Cargo bikes' limited capacity exacerbates these challenges. A failed delivery affects payload management, disrupts delivery routes, and adds time-consuming reloading efforts. Unlike larger vehicles, cargo bikes must efficiently balance payload distribution within tight delivery schedules. Addressing these issues requires targeted strategies to enhance delivery success rates for cargo bike couriers.

5.3.6 Cargo bike maintenance

Cargo bike maintenance plays a crucial role in ensuring the efficiency and reliability of deliveries. However, research tends to frame maintenance primarily as a cost factor, overlooking operational

and environmental influences that impact maintenance needs. Weather conditions, in particular, can significantly affect the frequency and complexity of maintenance interventions.

Most studies on cargo bike maintenance focus on its economic impact. Rajesh & Rajan (2020) and Aiello et al. (2021) analyze maintenance costs within the overall performance of delivery systems. Büttgen et al. (2021) distinguish between routine maintenance and repair activities, emphasizing the need to address both aspects systematically. Beyond cost considerations, external factors such as weather and road conditions play a major role in maintenance needs. Dybdalen & Ryeng (2021) observe that winter conditions in Norway lead to increased maintenance requirements. Similarly, Masterson (2017) highlights that in Seattle, poor road surfaces, hilly terrain, and a wet climate contribute to accelerated wear and tear on cargo bikes. Giordano et al. (2022) further reinforce that rain and snow significantly impact maintenance demands, though studies often lack granular data on specific maintenance issues caused by these conditions.

Despite the growing use of cargo bikes in urban logistics, little research explores their technical maintenance needs in depth. Key knowledge gaps include the frequency and types of breakdowns, the time required for repairs, and the effectiveness of preventive maintenance strategies. Further studies should also examine how different cargo bike configurations interact with payload weight and terrain challenges to optimize durability and reduce maintenance-related disruptions.

5.3.7 Identified gaps in the literature

Despite the growing body of research on cargo bike logistics, several key knowledge gaps persist across multiple dimensions of their operation. In cargo bike loading, studies fail to address how different bike configurations influence stability, battery performance, and weight distribution. Likewise, cargo bike safety remains understudied, particularly regarding musculoskeletal strain and ergonomic risks associated with item handling. Infrastructure-related research overlooks how cycling networks impact cargo bike routing efficiency and delivery success, particularly in winter and/or difficult riding conditions. Moreover, the security challenges of commercial cargo bike parking remain underexamined, with little data available on theft prevention measures or parking accessibility. Finally, while broader research on gig workers sheds light on customer interactions, there is a lack of dedicated studies on the social and logistical implications of cargo bike delivery failures. Addressing these gaps will be crucial for fostering a more resilient and efficient cargo bike delivery system.

5.4 Methodology

This section outlines the methodological approach used to analyze the role of cargo bikes in urban logistics. By combining statistical analyses, surveys, GPS tracking, and video observations, this research explores the factors influencing their adoption and operational performance. The methodology is designed to capture both quantitative and qualitative aspects, ensuring a comprehensive understanding of cargo bike logistics in different urban contexts.

5.4.1 Research framework

This study employs a mixed-methods approach to examine the role of urban infrastructure and rider preferences in cargo bike deliveries in Montreal. The research framework integrates quantitative and qualitative data collection methods, including surveys, on-site interviews, GPS tracking, and video observations. The survey was designed based on existing literature on cargo bike deliveries, winter cycling, and occupational health and safety for cyclists, targeting cargo bike riders engaged in first- and last-mile deliveries. In-depth and on-site interviews were conducted with riders during their delivery shifts to capture real-time decision-making processes related to route selection, parcel organization, and responses to delivery failures. GPS tracking data from Strava provided insights into cargo bike movement patterns, infrastructure usage, and trip characteristics, while video observations recorded rider behaviors, interactions with other road users, and delivery challenges in various weather conditions. The study spans from October 2022 to June 2023, with data collection procedures approved by the Research Ethics Board at Polytechnique Montréal and Université du Québec à Montréal (CÉR-2223-19-D). This comprehensive research design allows for a nuanced understanding of the operational strategies and challenges faced by cargo bike riders in an urban environment, informing policy recommendations for improved cycling infrastructure and delivery efficiency.

5.4.2 Data sources

The purpose of this sub-section is to present the various data sources employed in the study. These sources include surveys, on-site interviews, GPS track data and video data. Overall, the data collection procedure spans between October 2022 and June 2023.

5.4.3 Survey

The survey was conceived based on the main observations from the scientific literature on cargo bikes delivery, winter cycling and occupational health and safety for cyclists.

The bicycle design section explores rider protection features (e.g. roofs, side bars, additional lighting) and maintenance needs (e.g. frequency, reasons for maintenance). The working conditions section examines the impact of weather conditions (e.g. wind, cold, heat, rain, snow) on riders and road surfaces (e.g. ice, snow), road preferences for deliveries, common irritations (e.g. potholes, insufficient snow removal), perceived benefits (e.g.. improved physical and mental health, social recognition), and risks encountered (e.g.. collisions, loss of control when braking). The work organization section focuses on riders' autonomy and operational adjustments based on external factors. Lastly, the OHS section quantifies accidents, near-misses, and reports musculoskeletal and seasonal pains related to cycling work. Questions were tailored to address conditions across all four seasons. The survey was comprehensive, facilitating in-depth discussions during interviews, on-site visits, and delivery observations.

The target population consists of cargo bike riders involved in residential or commercial first- and last-mile deliveries, using cargo bikes with or without electric assistance. Food delivery couriers were excluded, as their work structure differs. An estimated 20 to 25 cargo bike riders met the inclusion criteria. The survey was conducted in October and November 2022. To ensure accessibility, a research team member was present on-site to assist participants, and the survey was made available in both French and English to comply with Canada’s language laws. A paper-based format was chosen to maximize response rates, as traditional paper surveys tend to yield higher participation compared to online surveys (Daikeler et al.. 2019).

A total of eight riders participated, representing approximately 30% of the target population. To maintain anonymity and avoid identifying their employers, participants were classified into two groups: (i) freight carriers, operating cargo bike fleets alongside vans and trucks, and (ii) "pure players", who rely exclusively on cargo bikes. All participants work in Montreal, with some sharing logistics spaces at the Colibri micro-hub and access to bike repair services. However, no consolidation practices were observed at the time of the survey. Participants' levels of experience are summarized in Tableau 5.1.

Tableau 5.1 Distribution of participants by years of experience

Years of experience	Participants working for main freight carriers	Participants working for pure players
<1	1	-
1-2	1	1
3-5	2	1
5 +	1	1
Total	5	3

5.4.4 Interviews

Given the technical nature of the research subject, interviews were conducted on-site during the delivery routes of cargo riders. A member of the research team shadowed participants over multiple days to observe their decision-making processes in real-time. The interview questions were informed by prior survey results and were designed to investigate key aspects of riders' operational strategies, specifically focusing on (i) route selection to the next destination. (ii) organization of parcels within the trailer, and (iii) strategies for managing delivery failures.

The data collection process consisted of three rounds of interviews conducted in October and November 2022, as well as April 2023. Interviews were conducted in situ while riders engaged in routine tasks such as trailer preparation or during pauses between deliveries. This methodological approach facilitated spontaneous responses and unrestricted communication. To ensure structured discussions and enhance the consistency of data collection, each interview round was centered around a specific theme. All interviews were audio-recorded for transcription purposes while maintaining participant anonymity in accordance with ethical guidelines. Furthermore, all interviews were conducted without managerial presence to mitigate potential response bias.

The first round of interviews examined how cargo riders organize and load parcels within their trailers to optimize delivery efficiency. This phase aimed to assess the level of expertise required for effective trailer loading despite pre-sorted parcel assignments for each route. Two riders participated: one with over three years of experience and another with less than one year. Participants were encouraged to verbalize their decision-making processes in detail, providing insights into the influence of experience on trailer organization strategies.

The second round of interviews focused on accidents and near-misses. Prior to participation, riders were informed of the potentially sensitive nature of the topic and given the option to withdraw. To align field experiences with academic definitions, riders were provided with operational definitions adapted from Quebec's Commission for Standards, Equity, and Occupational Health and Safety (*CNESST*): an accident was defined as "an event that causes injury to a person and/or damage to property", while a near-miss was defined as "an incident that does not result in injury or material damage." Participants were asked to reflect on their personal risk-taking behaviors and the mitigation strategies they employ to reduce accidents and near-misses. To structure the discussion, three categories of problematic situations were introduced: (i) adverse road conditions (e.g. snow accumulation, heavy rain, road construction), (ii) road-sharing challenges (e.g. interactions with motor vehicles, other cyclists, competing delivery services), and (iii) intersection-related risks (e.g. left turns, merging into traffic).

The third round of interviews was conducted during live delivery routes, focusing on strategies implemented when a recipient is absent. Riders were asked to identify the criteria considered in failed delivery scenarios, including factors such as street activity, neighborhood characteristics, and dwelling type. Each failed delivery scenario was documented (e.g. recipient absent, incorrect address) along with the decision-making process employed by riders. Additionally, the final resolution for each case was recorded, including options such as leaving the parcel at the door, entrusting it to a neighboring business, or reloading it into the trailer for redelivery. This multi-stage interview methodology provided comprehensive insights into the operational strategies of cargo riders, allowing for a nuanced understanding of their decision-making processes in real-world conditions.

5.4.5 Videos

To gain a comprehensive understanding of the delivery process, video recordings were conducted in April 2023 using sport-style camera equipment. The recordings spanned four days, capturing the real-world experiences of two cargo riders. Rider A wore the camera exclusively on their chest using a strap, while Rider B alternated between wearing the camera and mounting it on the handlebar of their cargo bike. A member of the research team accompanied the riders for three of the four days to conduct interviews and perform field observations.

Given the high frame rate selected for optimal video quality, the camera required frequent maintenance by the research team. On average, each cargo rider recorded approximately three hours of uninterrupted deliveries before battery replacement was necessary. Consequently, a research team member was present at the beginning of each workday to install the camera, at midday to replace the battery and memory cards, and at the end of the day to retrieve the equipment. Three distinct recording perspectives were utilized: the camera was either strapped to the chest of a research team member shadowing the cargo rider, strapped to the chest of the cargo rider, or mounted on the bike's handlebar (Figure 5.1).



Figure 5.1 Examples of camera installation

Each perspective (Figure 5.2) provided unique advantages and limitations. The first perspective, in which the camera was worn by the research team member, offered an external viewpoint of the delivery process, capturing parking strategies, parcel retrieval from the trailer, delivery execution, and road-sharing behaviors. Additionally, this method preserved the privacy of the cargo rider and customers. However, since the researcher followed the rider rather than experiencing the delivery firsthand, this setup did not capture the obstacles and real-time decision-making strategies encountered on the road. Furthermore, being shadowed by a researcher could be cumbersome for the cargo rider. The second perspective involved the camera being strapped to the cargo rider's chest. This setup was easy to use and did not interfere with delivery activities, providing detailed insights into real-time decision-making and the challenges faced on the road. However, due to the first-person viewpoint, extensive post-processing was required to redact sensitive information such

as home addresses and digital entry codes. Additionally, the cargo rider had to explain the purpose of the research project to inquisitive members of the public.

The third perspective involved mounting the camera on the bike's handlebar, which allowed for a stable focus on the road while maintaining privacy for both the cargo rider and customers.

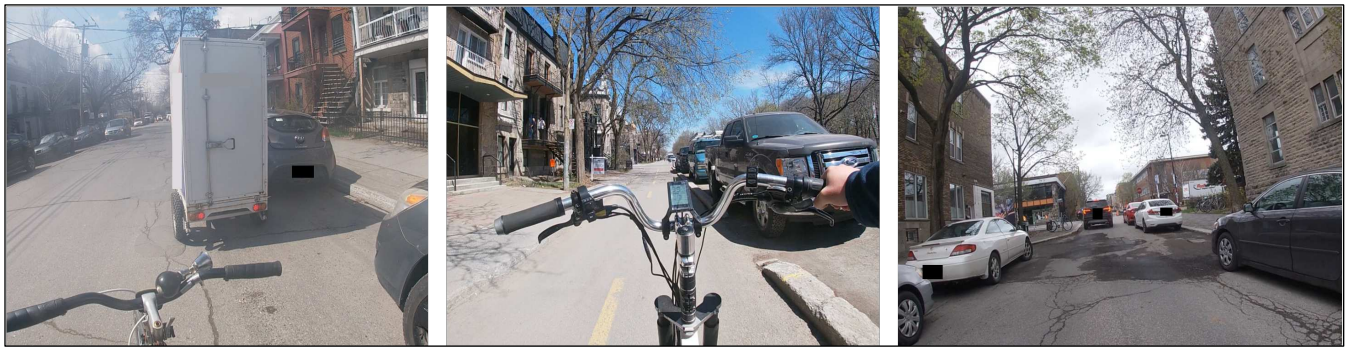


Figure 5.2 Examples of perspectives from the videos

However, due to the numerous potholes in the street of Montreal, the cargo rider needed to adjust the camera several time within a delivery tour.

5.4.6 GPS tracks

This section outlines the methodology for collecting and analyzing GPS tracks from cargo bike riders, detailing the data sources, extraction criteria, and key characteristics of the dataset.

GPS tracks were obtained using the sports tracking application Strava (*Strava*), a widely used platform that enables users to record, share, and analyze their physical activities. Strava supports activity tracking via smartphones and compatible devices such as smartwatches and sports belts. Users can maintain either public or private profiles and engage in group-based challenges or comparisons.

In scientific literature, Strava data has been utilized to study various aspects of cycling behavior. For example, Hong et al. (2020) examined the role of cycling infrastructure in mitigating the effects of adverse weather conditions in Scotland. Although concerns regarding data representativity exist, multiple studies (Hong et al., 2020; Jestico et al., 2016) have demonstrated a strong correlation between Strava data and official municipal cycling counts. Furthermore, Giordano et al. (2022) leveraged Strava data to evaluate the energy expenditure of cargo bike riders in several European cities. The present study adopts a methodology inspired by these works, as it has proven both

effective and reproducible. Strava collects and shares key performance metrics for each recorded activity, including total distance (km), moving time (hours), elapsed time (hours), elevation gain (meters), average speed (km/h), and maximum speed (km/h)**.** The elapsed time includes the total duration of an activity, encompassing breaks and stops, while moving time accounts only for periods when the user is in motion. Additionally, Strava provides downloadable activity maps along with segmented time and speed data Figure 5.3 (left). Users can also supplement their activity logs with personal notes and photographs. For this study, only GPS data related to cargo bike deliveries were considered. Relevant activities were identified based on at least one of the following criteria:

(i) the rider explicitly mentioned using a cargo bike in the activity description or referenced a specific cargo bike brand (e.g., "Bullitt," "Omnium");
(ii) the rider uploaded a photograph of a cargo bike in conjunction with the activity; or
(iii) the rider referenced a local cargo bike delivery company.

However, activities that met these criteria but also referenced food delivery services (e.g., "Uber Eats," "DoorDash") were excluded, as such work falls outside the scope of this study.

Data collection was limited to local cargo bike riders who maintained public Strava profiles and provided informed consent for their data to be used in this research. To ensure confidentiality, extracted data were formatted as GPX files without timestamps. Key metrics such as total distance, moving time, elapsed time, elevation gain, and average speed were retained, while participant identities were anonymized using coded identifiers. No other personal information was recorded. Given the variability in work schedules, data collection spanned from June 2021 to December 2022. All participants exclusively used human-powered cargo bikes**,** predominantly front-loaded models with an average payload capacity of approximately 90 kg (Figure 5.3, right).

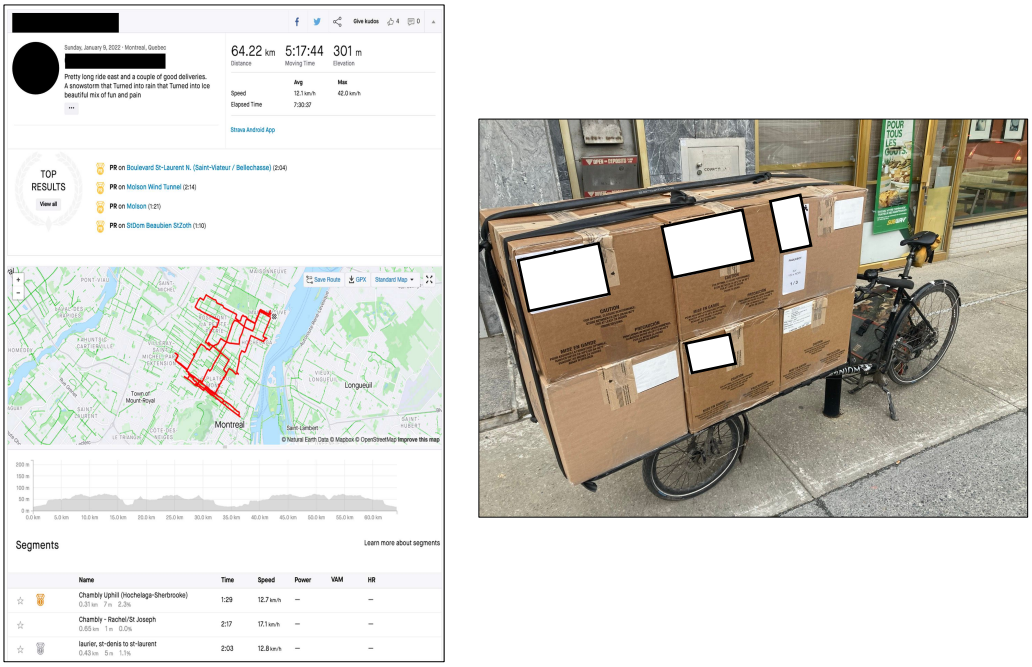


Figure 5.3 Strava activity (left) and loaded cargo bike (right)

A total of 108 GPS tracks were collected and analyzed from three participants who voluntarily recorded their delivery activities using Strava (Table 5.2). Only cargo delivery-related rides were included, ensuring that the dataset accurately reflects freight transportation.

Table 5.2 Distribution of collected GPS tracks by participants

Participant	Number of GPS tracks collected	Timeframe
P1	5	September 2022 – October 2022
P2	10	June 2021 – December 2022
P3	93	June 2021- December 2022
Total	108	

5.4.7 Data treatment

The treatment of data is an important step in ensuring the accuracy and relevance of the analyses conducted in this research. This subsection describes the processes applied to clean, structure, and analyze data from multiple sources, including GPS trajectories, and video observations. The

integration of these diverse datasets enables a nuanced assessment of infrastructure use and operational challenges in cargo bike logistics.

- Video time stamping

To systematically analyze the sequential actions within each delivery process, time stamps were applied to video recordings. This method allowed for a precise breakdown of sub-activities, making it easier to track, categorize, and quantify each stage of the delivery. By segmenting the footage into distinct phases, such as retrieving the package, biking, walking to and from the delivery location, waiting at the door, interacting with customers, and reorganizing the cargo bike etc., this approach provided a granular understanding of time allocation during deliveries.

- Map matching

Map matching is a crucial step in processing GPS data, ensuring that raw positional data aligns accurately with the road network. Given the inherent inaccuracies of GPS signals due to signal drift, sampling intervals, map matching corrects these deviations by snapping recorded GPS tracks to the most plausible road segments. Also, given the specific context of deliveries which are recorded through *Strava* and with a device sometimes in the pocket of the cargo rider, GPS tracks tend to stop and deviate from the road to go near buildings (see Figure 5.4).

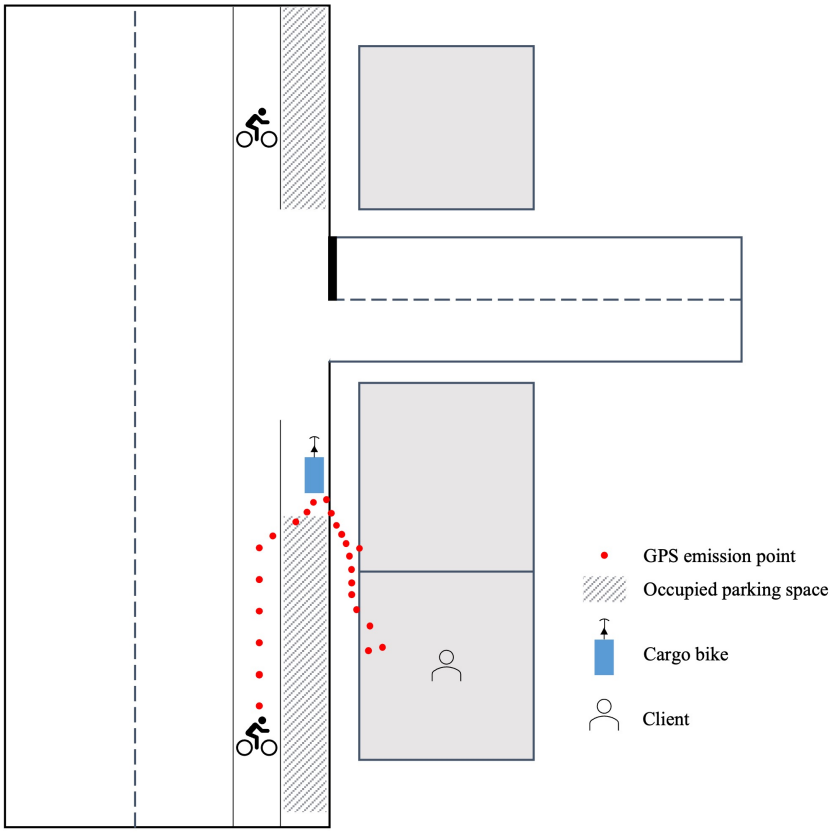


Figure 5.4 Example of GPS tracks deviation due to a delivery activity

For this study, MappyMatch (L. Zhu et al., 2017), an open-source Python library developed by NREL, was employed to refine cargo bike trajectories. The algorithm leverages a Hidden Markov Model (HMM) to probabilistically determine the most likely path taken by the rider, considering road geometry, movement constraints, and historical data. This approach enhances the reliability of GPS-derived insights, ensuring accurate identification of infrastructure use and route preferences in urban environments.

- Stop identification

Stop identification is essential for analyzing cargo bike delivery patterns, as it distinguishes active travel segments from stationary periods where deliveries or other activities occur. To achieve this, MovingPandas, a Python library for trajectory analysis, was used to detect stops within the GPS tracks (Graser, 2019). The stop detection algorithm was configured with a delta distance threshold of 30 meters, based on the work of Dalla Chiara et al. (2023), ensuring that only meaningful stops, rather than minor positional fluctuations, were considered. Additionally, a delta time threshold of 1.15 minutes to 10 minutes was applied to differentiate short delivery-related stops from longer breaks. This method enabled a precise classification of stop locations (Figure 5.5).

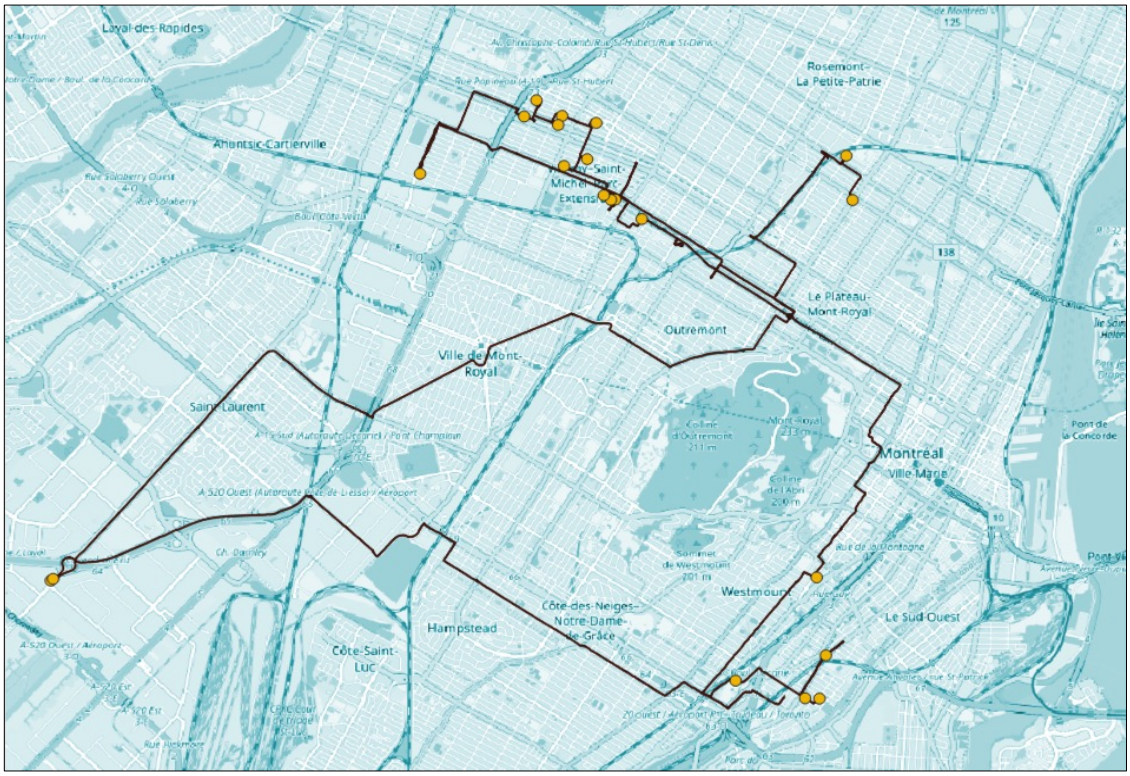


Figure 5.5 Example of stops identified in a delivery tour

5.5 Results

This section presents the key findings from the analysis of cargo bike deliveries performed in the city of Montreal. By examining operational performance, infrastructure interactions, and rider preferences, the results highlight the main opportunities and challenges associated with this alternative delivery mode. The insights gained contribute to a better understanding of their potential for sustainable urban freight transportation.

5.5.1 Classification of item movements when loading a cargo bike

Cargo bike loading requires multiple parcel manipulations due to space constraints. On average. each parcel is handled 2.46 times before being fully loaded into the bike. To analyze the distribution of time spent on different loading activities. video recordings of cargo bike loading processes are categorized into four distinct movement types: (1) *Itemizing the load*. which involves unloading parcels from the pallet and strategically positioning them for loading; (2) *Loading*. where parcels are placed inside the cargo bike; (3) *Repositioning*. which includes relocating parcels within the bike. removing and reloading them. or temporarily placing them on top of the bike; and (4) *Exchanges*. where riders swap parcels based on route optimization knowledge. The proportion of time spent on each movement type is summarized in Table 5.3.

Table 5.3 Proportion of time spent on different manipulation operations

Type of parcel movement	Proportion of the time
Itemizing the load	60.62 %
Loading the bike	21.94 %
Repositioning	6.22 %
Exchanges	1.22 %

The results indicate that the majority of the time (60.62%) is allocated to itemizing and preparing parcels before they are loaded into the bike. suggesting that pre-loading organization is a critical phase of the cargo bike loading process. In contrast. the actual loading accounts for 21.94% of the total time. while repositioning and exchanges contribute to a smaller fraction. at 6.22% and 1.22%. respectively. These findings highlight the significance of optimizing itemization and pre-loading strategies to improve efficiency in cargo bike operations.

5.5.2 Planning the ride based on preferences and risk perceptions

Cargo bike riders rely on first-hand experience to plan their delivery routes, considering factors such as infrastructure preferences, perceived risks, and seasonal variations. This subsection presents survey findings on route selection and infrastructure use in Montreal.

Montreal's cycling network includes three main types of bike lanes: the Réseau Express Vélo (REV), four-season bike lanes, and regular bike lanes. The REV, a 191 km project launched in 2020, features wide, physically separated lanes, with 23 km currently operational. Four-season bike lanes receive year-round maintenance, including snow removal and de-icing, while regular bike lanes are maintained only from April to November (Table 5.4).

Table 5.4 Length of bikelanes by category of bikelane infrastructure

Type of bike lane infrastructure	2024
REV	23 km
Four seasons	694 km
Regular	184 km
Total	901 km

Surveyed cargo riders favor the REV and four-season bike lanes, particularly in summer, citing the additional width that facilitates overtaking and road-sharing (Figure 5.6). Car lanes rank second in preference, followed by regular bike lanes, while back alleys and sidewalks are used the least. In winter, the use of car lanes increases, likely due to ice accumulation on bike lanes, colloquially called "turtles" by Montreal riders. Back alleys become even less viable due to inconsistent snow removal. Notably, some respondents assigned identical rankings to multiple infrastructure types, explaining why response totals in Figure 5.6 may not match the number of participants. Sidewalk use remains consistently low across seasons, reflecting a general reluctance among cargo riders to use pedestrian spaces.

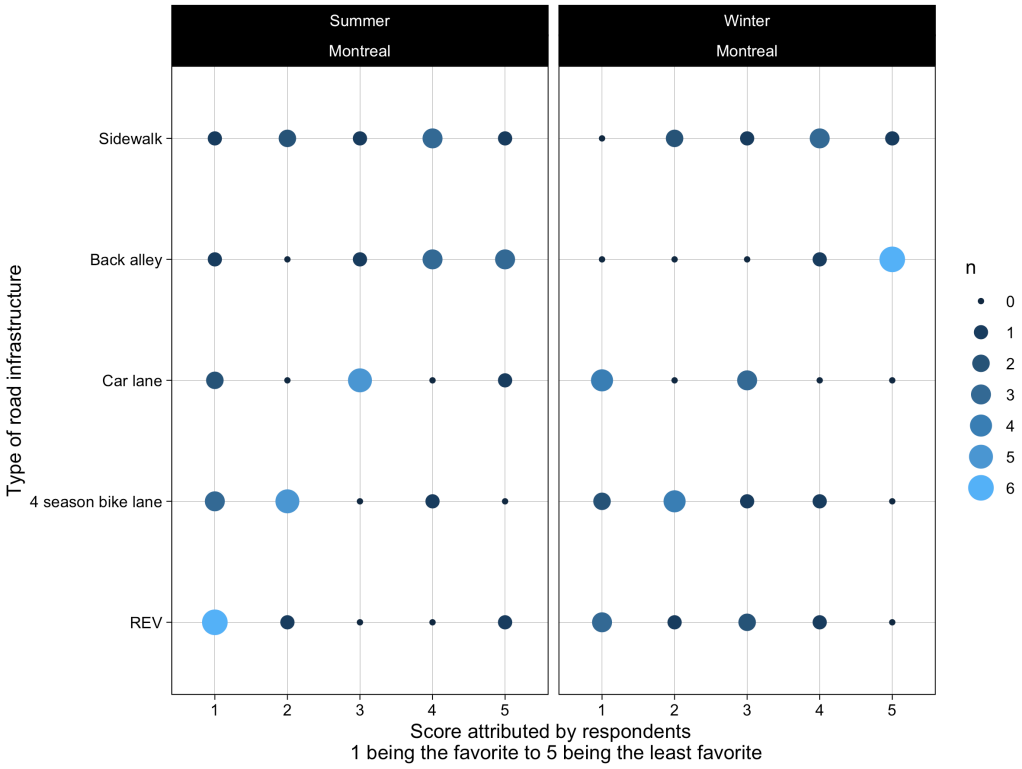


Figure 5.6 Preferences in biking infrastructure by season for cargo-bike riders

Risk perception influences infrastructure choices (Figure 5.7). In summer, cargo riders report higher risks of collisions with cars, pedestrians, and cyclists due to increased bike-sharing users and pedestrian-only streets where cargo bikes are permitted. In winter, the primary concerns shift to loss of braking control and vehicle collisions, exacerbated by icy conditions.

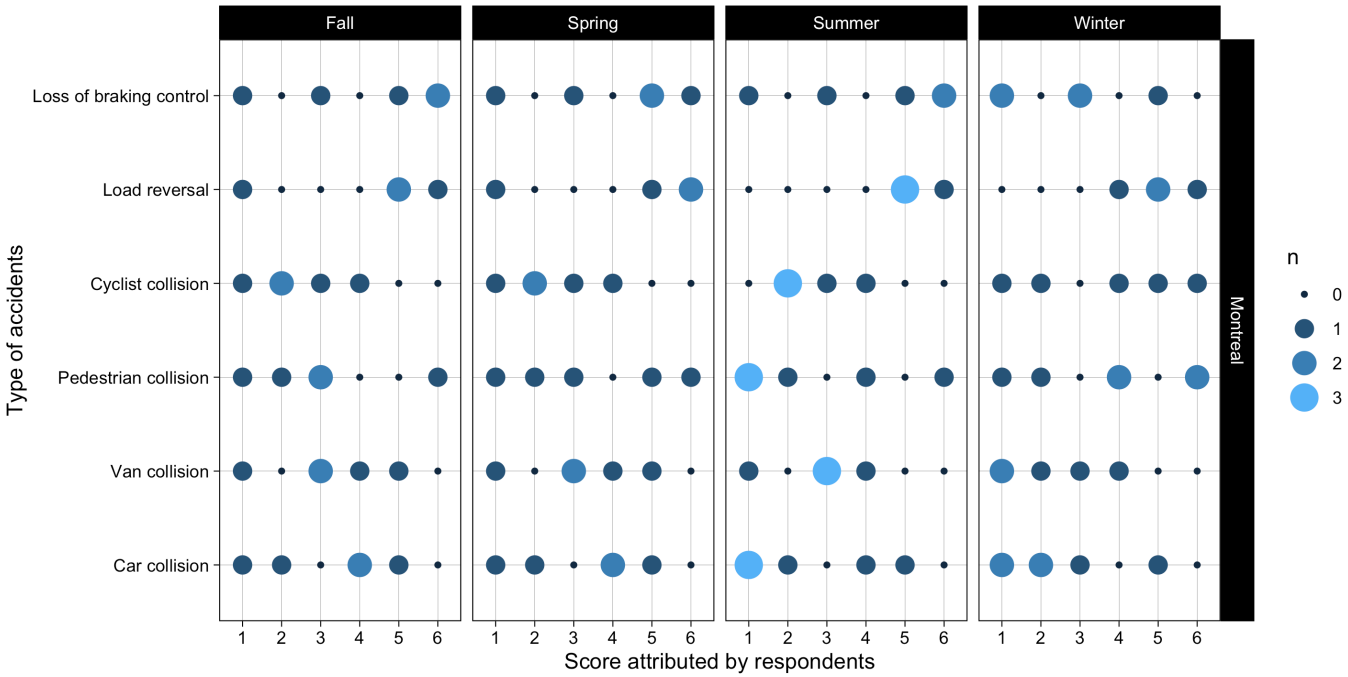


Figure 5.7 Assessed risk by type and by season identified by cargo riders

Across all seasons, load instability is not a significant concern, likely due to the increasing use of trikes, which provide greater stability. However, risk perception contrasts with ease of road-sharing (Figure 5.8). While riders acknowledge a higher risk of collisions in summer, they also find it easier to share the road compared to winter. Over 75% of respondents rate road-sharing as "rather easy" to "neutral" in summer, whereas in winter, over 75% report it as "rather difficult" to "very difficult". The difficulty of winter road-sharing can be attributed to reduced bike infrastructure availability and maintenance, forcing cargo riders to use car lanes. Additionally, accident probability is perceived to be highest in fall and winter, emphasizing the need for improved winter maintenance and infrastructure adjustments.

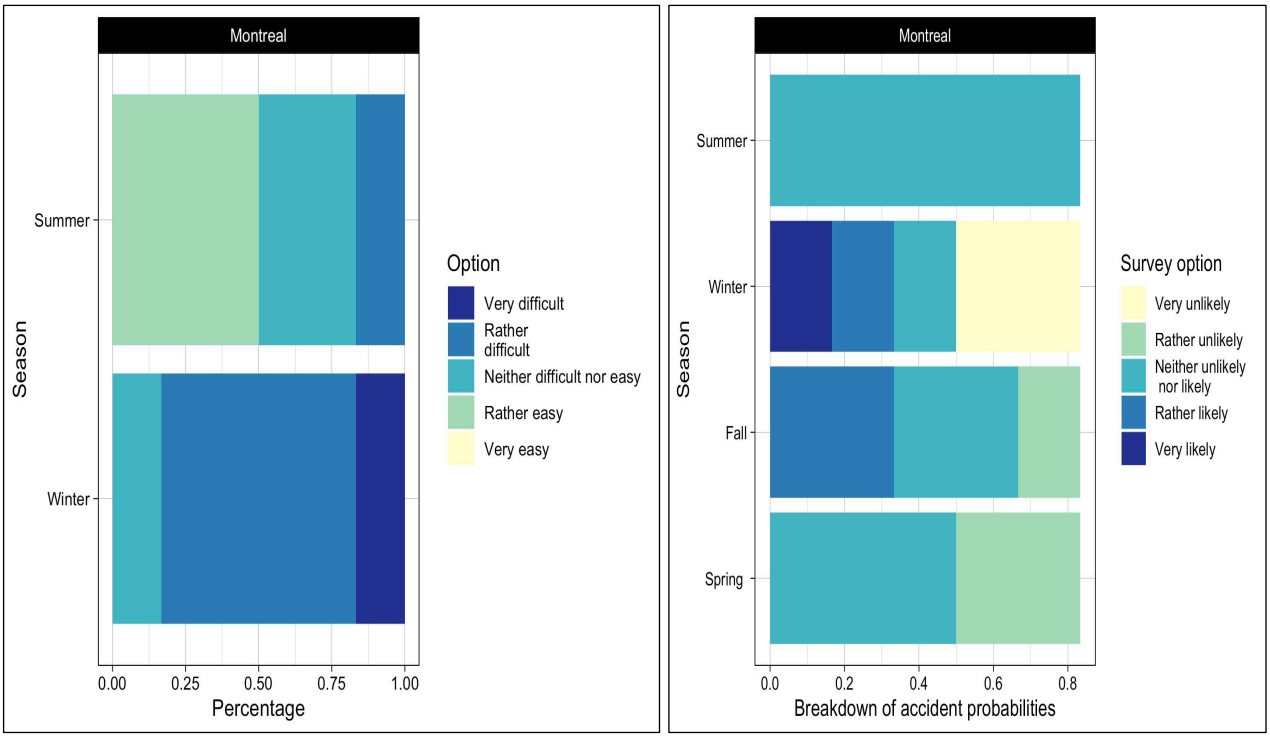


Figure 5.8 Road-sharing difficulty perception by season (left) and assessed accident probability by season (right)

5.5.3 Cargo bike riders' use of cycling infrastructure : patterns and seasonal variations

From the planification of the tour to the actual deliveries. cargo riders use the infrastructure in different ways. This section analyzes GPS and observational data to assess the extent of bike lane usage in cargo bike delivery operations and explores seasonal variations in infrastructure reliance.

Figure 5.9 presents a heatmap of all GPS tracks collected, covering primarily Montreal and parts of its neighboring municipalities. This visualization provides a spatial representation of the most frequently used routes and highlights the extent to which riders utilize cycling infrastructure.

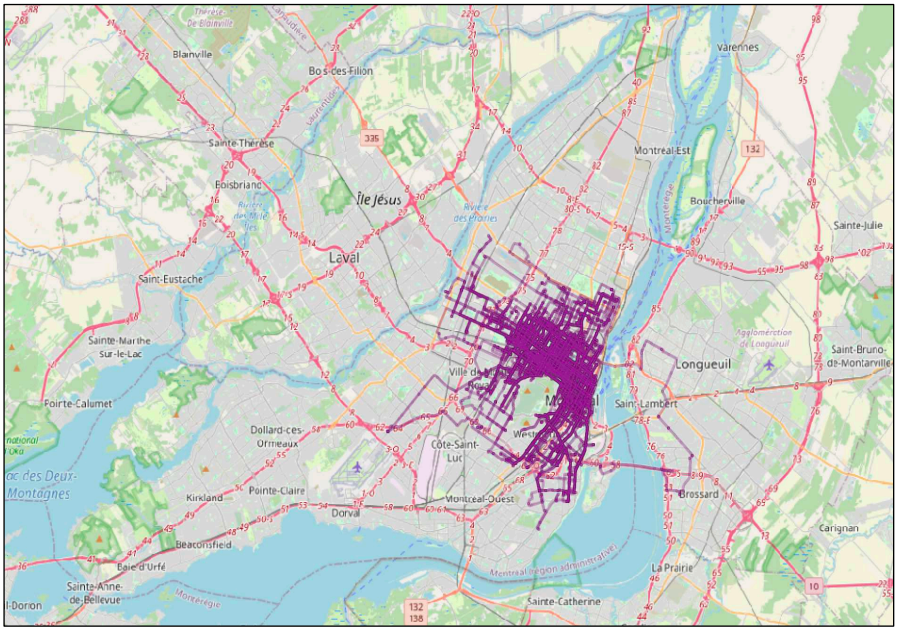


Figure 5.9 GPS points from the 108 tracks collected

An analysis of road coverage within the study area reveals that bike lanes constitute 28.26% of the total road network (Table 5.5). The analysis of delivery tours indicates that, on average, 26.24% of the total traveled distance occurs on bike lanes (Table 5.6). The moderate standard deviation (9.87%) suggests variability in infrastructure use across different routes. While some delivery tours make minimal use of bike lanes (4.70% at the lowest recorded proportion), others rely heavily on them, with a maximum observed proportion of 59.38%. The median value of 24.65% indicates that at least half of the delivery trips allocate around a quarter of their distance to bike lanes.

Table 5.5 Length in km by type of road

Type of road	Total length (km)
Bike lane	228.6
Car lanes (excluding back alleys and service roads)	808.86

The variability in bike lane usage is further influenced by seasonality. Table 5.6 presents the proportion of distances spent on bike lanes in different seasons, showing notable differences in usage patterns.

Table 5.6 Proportion of distances spent on bike lanes without and with seasonality

	Count	Mean	Std. Dev.	Min	25 %	50 %	75 %	Max
Length on bike lanes without seasonality (in %)	108	26.24	9.87	4.70	20.20	24.65	30.08	59.38
Length on bike lanes during winter (in %)	13	21.75	5.51	11.78	18.65	19.97	27.06	29.67
Length on bike lanes during spring (in %)	43	26.89	9.95	4.70	20.60	25.00	31.70	50.94
Length on bike lanes during summer (in %)	42	27.03	11.43	10.47	19.52	24.34	31.25	59.38
Length on bike lanes during autumn (in %)	10	25.94	5.24	13.99	24.35	27.19	28.77	31.80

The data highlights seasonal fluctuations in bike lane utilisation. In autumn, the mean percentage of travel distance spent on bike lanes is 25.94%, with a relatively low standard deviation (5.24%), indicating more consistent infrastructure usage. The interquartile range (24.35% to 28.77%) suggests that most delivery trips moderately rely on bike lanes in this season. Spring sees a slightly higher mean bike lane usage of 26.89%, with greater variability (standard deviation of 9.95%). The minimum observed value of 4.70% indicates that some tours barely use bike lanes, while the maximum of 50.94% suggests extensive reliance on cycling infrastructure in well-connected areas. Summer follows a similar trend, with the highest mean bike lane usage (27.03%) but also the greatest variability (standard deviation of 11.43%). The interquartile range (19.52%–31.25%) and a maximum value of 59.38% suggest that some riders take significant advantage of cycling infrastructure during this season. Winter, however, exhibits the lowest mean bike lane usage (21.75%), with reduced variability (standard deviation of 5.51%). The median value of 19.97% and an interquartile range of 18.65% to 27.06% highlight the impact of adverse weather conditions, which may force riders to rely more on car lanes. The presence of ice and snowbanks after snowstorms further limits the usability of bike lanes, leading to constrained cycling routes.

When compared to existing literature, the findings for Montreal align closely with studies conducted in winter-prone regions. A study by Dybdalen & Ryeng (2022) in Norway reported that

cargo riders utilized bike lanes for 35.81% of their trips, with 26.80% in winter and 45.77% in spring. Despite Montreal's relatively lower winter cycling network coverage, the results suggest similar seasonal trends, reinforcing the need for improved winter maintenance and infrastructure expansion.

Riding speed is a key indicator of the efficiency of cargo bike deliveries. Table 5.7 presents speed variations across different seasons.

Table 5.7 Speed (km/h) without and with seasonality for cargo riders

	Count	Mean	Std. Dev.	Min	25 %	50 %	75 %	Max
Average speed without seasonality (in km/h)	108	19.07	3.18	4.10	17.97	20.05	21.30	23.10
Average speed during winter (in km/h)	13	14.48	2.73	9.90	12.10	14.60	17.10	18.2
Average speed during spring (in km/h)	43	19.75	2.00	14.4	19.15	20.00	21.05	22.9
Average speed during summer (in km/h)	42	20.56	1.75	12.0	20.02	20.75	21.47	23.1
Average speed during autumn (in km/h)	10	15.76	4.77	4.1	14.93	16.10	18.95	20.4

Winter conditions significantly reduce the average cycling speed (14.48 km/h), with a much lower median speed (14.60 km/h) and a narrower interquartile range. The reduction in speed is largely attributed to poor road conditions, particularly snow, ice, and slush accumulation, which limit maneuverability and force riders to adopt a more cautious approach (refer to Figure 5.10 for more winter irritants). Additionally, riders often avoid bike lanes in winter due to inadequate maintenance, further slowing their travel when sharing lanes with motorized traffic. Conversely, summer offers the most favorable conditions, with the highest mean speed (20.56 km/h) and the lowest variability (standard deviation of 1.75 km/h). The smooth road conditions, increased daylight, and better bike lane availability contribute to higher efficiency in cargo bike deliveries. Autumn presents a unique case, where riders experience significant speed fluctuations (standard deviation of 4.77 km/h), likely due to variable weather conditions such as rain and early frost. The lower mean speed (15.76 km/h) suggests that certain days require slower, more careful navigation, particularly during seasonal transitions when road conditions can be unpredictable. When compared to the literature, the study in Norway by Dybdalen & Ryeng (2022) reports an overall average speed of 12.77 km/h for cities in Norway, significantly lower than the 19.07 km/h recorded in Montreal. Their findings indicate a 15.33 km/h average speed during spring (19.75 km/h in

Montreal) and 11.10 km/h during winter (14.48 km/h in Montreal). This discrepancy can be partially attributed to Montreal's wider roads, which may allow for better maneuverability and fewer physical constraints compared to the narrower streets often found in Norwegian cities. Additionally, differences in winter maintenance strategies and urban cycling culture may contribute to variations in speed performance across both regions.

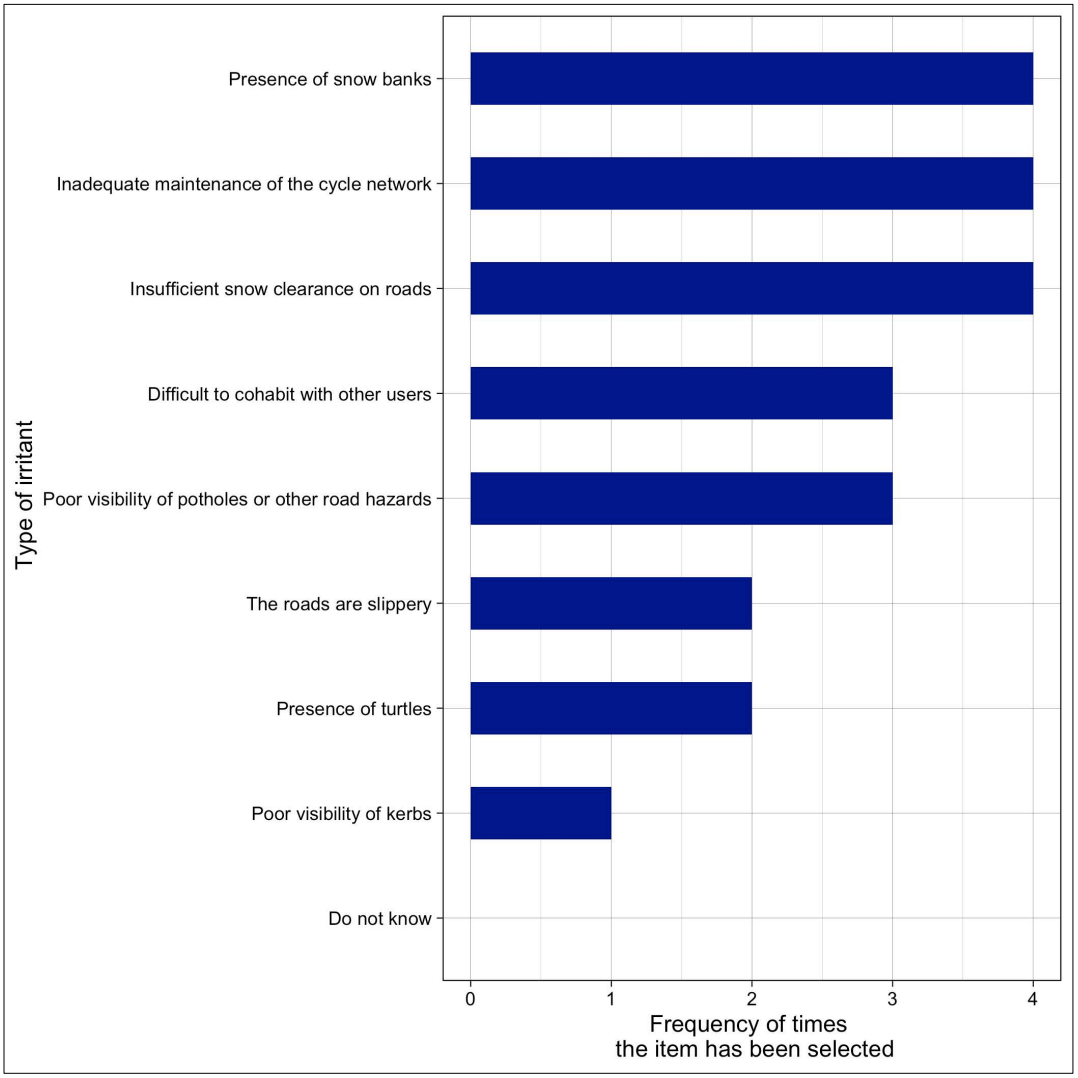


Figure 5.10 Main irritants during winter time

Cargo bike riders in Montreal demonstrate moderate reliance on bike lanes, with notable seasonal variations. While summer and spring allow for higher infrastructure usage, winter conditions significantly hinder bike lane accessibility and reduce average cycling speeds. The findings emphasize the need for improved cycling infrastructure and maintenance, particularly in winter, to

ensure the efficiency and safety of cargo bike deliveries. Addressing these challenges will be crucial for the continued adoption of sustainable urban logistics solutions.

5.5.4 Observed parking behavior

This subsection examines cargo riders' parking choices based on stated preferences, camera observations, and comparisons with existing literature**.** The results from interviews are analyzed alongside direct observations to assess how cargo riders adapt their parking strategies in urban environments.

During interviews, cargo riders were asked to rank their perception of different road users which are pedestrians, cyclists, other delivery services (e.g., vans, postal workers), public transport (especially buses), and private cars on a three-point scale: negative, neutral, or positive**.** They also indicated how often they parked in spaces reserved for each category, such as sidewalks (pedestrians), bike lanes (cyclists), and bus stops (public transport). The options for respondents were (i) "I never use this space to park or I strongly try to avoid this space" (coded -1), (ii) "I

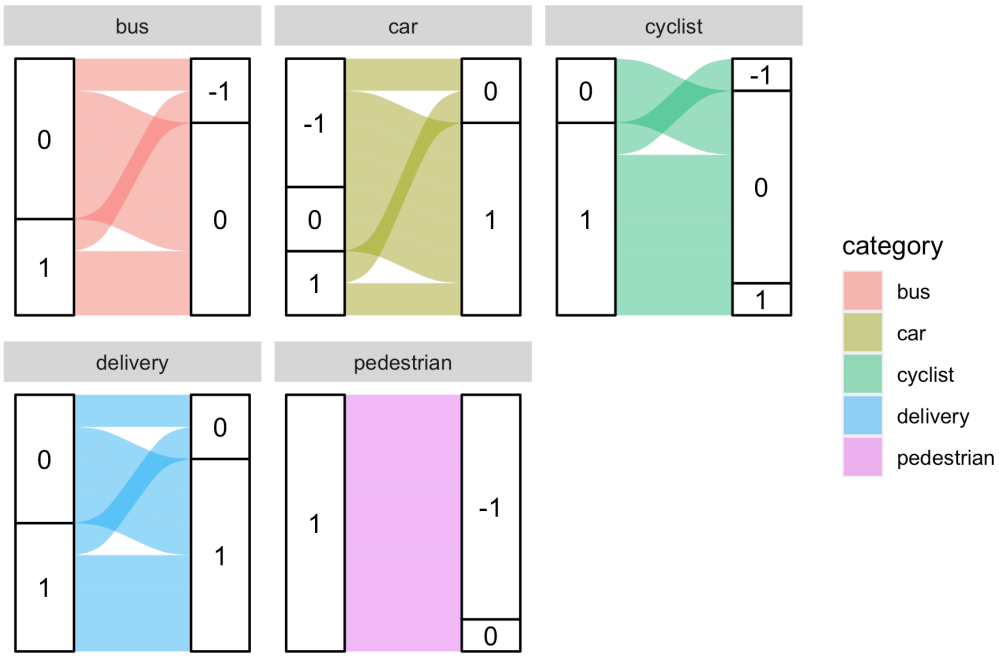


Figure 5.11 Relation between perception of different users and frequency of use of parking strategy

sometimes use this space to park" and (coded 0) (iii) "I often use this space to park or I actively seek this space to park" (coded +1). The results (Figure 5.11) show predominantly positive

perceptions of pedestrians and cyclists, while views on private cars are more polarized, with half of respondents expressing negative opinions. Cargo riders tend to avoid sidewalks for parking, recognizing that their wider bikes could obstruct pedestrians. Some report using the edges of bike lanes for convenience but acknowledge that this can hinder passing cyclists.

The use of bus lanes elicits mixed reactions, some riders find them practical since they are generally free of parked cars, but others report difficulties exiting when buses arrive. When it comes to car parking spaces, riders show little hesitation in using them, with one participant remarking: “When it comes to cars, everything is fair game”. The perception of other delivery services is generally neutral or positive, though some riders report occasional verbal or physical aggression, particularly when using reserved delivery spaces.

Camera observations largely confirm the self-reported strategies. The majority of cargo riders (81.69%**)** park in regular car spaces, while 7.04% use bus stops, and 4.23% park in bike lanes. Additionally, 11.27% of parking events occur in off-street locations, such as back alleys or near bike rental station. Back alleys are primarily used to avoid disrupting businesses, particularly restaurants during peak hours. Interestingly, no instances of sidewalk parking were

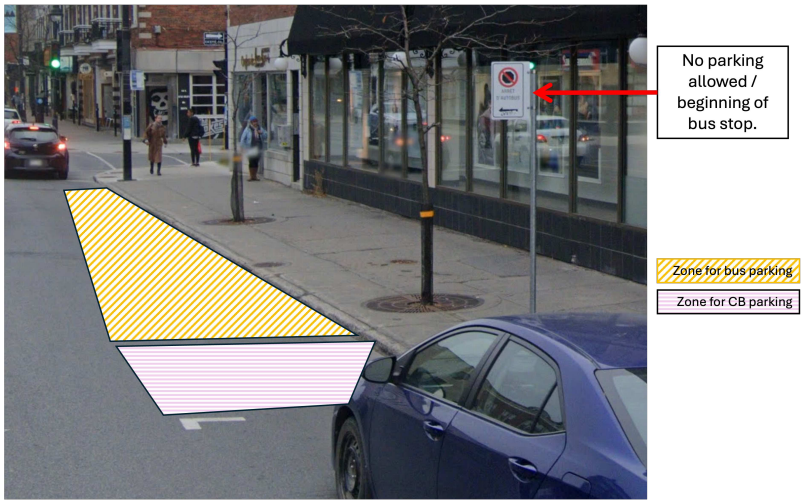


Figure 5.12 Illustration of the 'grey' space between car parking and a bus stop

observed, even though some riders mentioned this option in surveys. When using bus stops, riders tend to park in "grey areas" between car parking zones and bus lanes rather than directly in the path of buses (Figure 5.12). Despite some survey respondents indicating they frequently use delivery zones**,** no such instances were recorded during observations.

These findings contrast with Dalla Chiara et al. (2023), where cargo riders were observed **parking** on sidewalks 79.9% of the time **(**Table 5.8**)**. That study also reported higher use of curbspace and loading zones, suggesting significant differences in parking norms and infrastructure availability between cities. One possible explanation for this discrepancy is Montreal's stronger cycling culture, where sidewalk parking may be less acceptable. Additionally, the presence of a researcher following riders during video recording could have influenced parking behavior**,** leading them to choose more formal parking options.

Table 5.8 Comparison between parking behaviors

	(Dalla Chiara et al., 2023)	This study
Percentage of time spent parking on the sidewalk	79.9 %	0 %
Percentage of time spent parking on a bus zone	0.84 % (4.8 % of 17.5%)	7.04 %
Percentage of time spent parking on paid parking	5.88 % (33.6 % of 17.5 %)	81.69 %
Percentage of time spent parking on commercial vehicle load zone	0.40% (2.3 % of 17.5%)	0 %

These results highlight how infrastructure, policy enforcement, and cultural attitudes influence cargo riders' parking choices. Further research is needed to assess how urban regulations and enforcement impact their decision-making**.** Moreover, given the strong influence of local cycling culture, the generalizability of these findings warrants further discussion. The extent to which these results can be applied to other urban contexts depends on factors such as the maturity of cycling infrastructure, the political will to enforce cycling-related regulations, and the societal perception of cargo bike use. Future studies should therefore consider cross-contextual comparisons to better understand how these variables interact in different cities or countries.

5.5.5 Walking, carrying and handing out the parcels

Some steps of a cargo bike delivery, involving walking with parcels, waiting, and handing them over, are often overlooked in efficiency analyses. However, these tasks significantly contribute to the physical strain on cargo bike riders and the overall time spent on deliveries. By analyzing video footage, we can retrace the hidden yet critical sub-activities involved in the delivery process.

From the moment a rider retrieves a package from the cargo bike to its final handoff, several actions unfold in sequence. First, the rider must locate the correct parcel within the bike's storage, a process that varies in duration depending on load organization. The average time for this task is 51 seconds, though it can take as little as 13 seconds or extend to 130 seconds (Table 5.9). Once the package is secured, the rider walks to and from the delivery point, averaging 134 seconds per trip, with a considerable range from 10 to 312 seconds. For residential deliveries, waiting at the door is another time-consuming step, averaging 89 seconds, though it can last up to 249 seconds. Business deliveries require less waiting but involve time inside the establishment, averaging 60 seconds. Once the delivery is complete, the rider returns to the cargo bike, often needing to rearrange parcels to prepare for the next stop, a task that takes an average of 135 seconds.

Moreover, additional physical challenges can arise. Out of the 82 deliveries observed, 26 required the rider to climb exterior stairs (31.70%), and 13 involved heavy parcels (15.85%). These factors increase the physical demands of the job, contributing to fatigue and potential musculoskeletal strain.

Understanding the time distribution of these tasks highlights the inefficiencies and physical burdens associated with last-mile cargo deliveries. Future research should consider strategies to optimize parcel retrieval and handling, potentially integrating ergonomic solutions or delivery support tools to ease the physical strain on riders and enhance overall efficiency.

Table 5.9 Time (in seconds) for each sub-activity within the delivery process

	Count	Mean	Std. Dev.	Min	25%	50%	75%	Max
Looking for the package in the bike (seconds)	82	51	33	13	36	41	61	130
Walking to and from the destination (seconds)	82	134	94	10	58	117	216	312
Waiting at the door (seconds)	51	89	73	11	25	62	147	249
Delivering within a business (seconds)	31	60	150	15	19	40	147	167
Rearranging the packages in the cargo bike (seconds)	82	135	68	87	107	145	179	181

5.6 Conclusion

This study provides an in-depth analysis of the role of urban infrastructure and riders' preferences in cargo bike deliveries in Montreal, highlighting critical operational challenges and infrastructure interactions. Through a mixed-methods approach combining surveys, GPS tracking, interviews, and video observations, the research identifies how delivery riders navigate urban spaces, interact with existing infrastructure, and adapt to seasonal variations.

5.6.1 Main findings

Key findings indicate that cargo bike deliveries present a viable and sustainable alternative to traditional motorized delivery modes, particularly in dense urban areas. The study underscores that dedicated cycling infrastructure, such as the Réseau Express Vélo (REV) and four-season bike lanes, significantly enhances cargo bike efficiency and safety. However, it also reveals a discrepancy between existing infrastructure and the needs of cargo bike riders, particularly in winter conditions. Riders frequently resort to using car lanes due to inadequate snow removal and infrastructure maintenance, increasing the perceived risk of collisions and reducing delivery efficiency. Moreover, parking strategies, another critical component of cargo bike operations, remain a challenge due to limited designated spaces and competition with motorized vehicles. This study provides empirical evidence of the operational constraints faced by cargo bike riders, offering new insights into the logistics of last-mile deliveries. By analyzing how riders interact with infrastructure, the study contributes to the broader discourse on urban freight sustainability. The research also advances knowledge on cargo bike parking behaviors, an area often overlooked in literature, by comparing observational data with self-reported rider preferences.

5.6.2 Policy implications

The findings of this study offer valuable insights for policymakers and freight carriers aiming to improve the efficiency and sustainability of cargo bike deliveries. Municipal authorities should prioritize expanding and maintaining dedicated cycling infrastructure, including year-round bike lanes and micro-hubs for cargo bike parking and consolidation. Improved snow removal from bike lanes and targeted policies for integrating cargo bikes into existing freight regulations would enhance operational efficiency and safety. Additionally, policymakers can incentivize cargo bike adoption through subsidies, tax benefits, or pilot programs supporting logistics operators

transitioning to greener delivery modes. Freight carriers can optimize delivery routes by leveraging real-time infrastructure data and adapting scheduling strategies to accommodate seasonal variations. Collaboration between cities and logistics providers is essential to establish standardized parking and loading zones that minimize disruptions to urban mobility while maximizing cargo bike utility. By implementing these policies, cities such as Montreal can foster a more resilient, low-emission urban freight system that aligns with broader sustainability goals.

5.6.3 Limitations

Despite its contributions, this study has some limitations. The sample size for survey responses, though representative of the local cargo bike delivery ecosystem, remains small, which may limit the generalization of certain findings. Additionally, the reliance on GPS data from a limited number of participants may not capture the full diversity of cargo bike operations across different urban contexts. Another limitation is the focus on Montreal, as findings may not be directly transferable to cities with different urban layouts, regulatory environments, and climatic conditions. The study also does not assess long-term economic viability, an important factor in determining the scalability of cargo bike logistics.

5.6.4 Future research

Future research should address these limitations by expanding the scope of data collection to include a broader sample of cargo bike riders across multiple cities and climatic conditions. Research into infrastructure adaptation for cargo bike deliveries, such as dedicated parking zones and improved winter maintenance strategies, is also needed to facilitate wider adoption. Moreover, route optimization services could customize the route planning on riders' specific preferences. Finally, integrating real-time rider feedback into urban planning initiatives could enhance the effectiveness of policies designed to support sustainable last-mile logistics.

Overall, this study contributes to the growing body of literature on cargo bike logistics by providing empirical evidence on operational challenges and infrastructure use. By addressing identified limitations and expanding future research directions, cargo bike deliveries can become a more robust and scalable solution for sustainable urban logistics.

CHAPITRE 6 ARTICLE 3 : « ASSESSING THE POTENTIAL OF CARGO-BIKES FOR MEDIUM-SIZED CITIES USING OPEN DATA »

Cet article est soumis dans le journal « *Journal of Cycling and Micromobility* » (le 31 mars 2025).

ASSESSING THE POTENTIAL OF CARGO-BIKES FOR MEDIUM-SIZED CITIES USING OPEN DATA

Suzanne Pirie, Martin Trépanier, Walter Rei

6.1 Abstract

Urban freight transport plays a crucial role in sustaining economic activities, yet its reliance on conventional motorized vehicles contributes to traffic congestion, air pollution, and greenhouse gas emissions. As cities seek sustainable alternatives, cargo bikes emerge as a promising solution for last-mile deliveries, offering environmental and operational benefits compared to traditional delivery trucks. While extensively studied in large metropolitan areas, the potential of cargo bikes in medium-sized cities remains largely underexplored. These cities, characterized by lower population densities and distinct freight flow patterns, present both unique challenges and opportunities for cargo-bike logistics. This study introduces a methodology to assess the feasibility of cargo-bike deployment in medium-sized cities by leveraging open data and a multi-criteria framework. The approach integrates spatial analysis of population density, land use, cycling infrastructure, and climate data to identify cities best suited for cargo-bike logistics. A hierarchical clustering method, combined with a scenario-based assessment, categorizes cities based on key urban and logistical characteristics. An expert-driven Delphi survey refines the weighting of assessment criteria, ensuring a robust evaluation. Additionally, a ranking system prioritizes cities for pilot implementation based on their suitability for cargo-bike delivery initiatives.The findings offer a structured framework to determine the suitability of cargo-bike logistics across different medium-sized urban settings, providing insights for policymakers and urban planners seeking to promote sustainable freight solutions.

Key-words : medium-sized cities, cargo bike, urban logistics, alternative logistics

6.2 Introduction

Urban freight transport plays a crucial role in sustaining economic activities, yet its reliance on conventional motorized vehicles contributes to traffic congestion, air pollution, and greenhouse gas emissions. In 2019, 26 % of freight was transported by trucks (De Bruycker, 2023). However, 84 % of the GHG emissions for the transportation of freight are coming from road transportation modes (De Bruycker, 2023). Moreover, the spectacular rise of e-commerce sales has increased the demand for home deliveries within cities. In Montreal, around 900,000 deliveries are allegedly done each day, including packages, food deliveries and at home meal kits (Meloche et al., 2025).

As cities seek sustainable alternatives, cargo bikes emerge as a promising solution for last-mile deliveries, offering environmental and operational benefits compared to traditional delivery trucks (Narayanan & Antoniou, 2022a; M. Sheth et al., 2019). While cargo bikes are widely studied in the context of large metropolitan areas, their potential in medium-sized cities remains largely underexplored. Medium-sized cities, characterized by lower population densities and distinct freight flow patterns (Delaitre et al., 2009; Flora et al., 2019), present both unique challenges and opportunities for cargo-bike logistics. Existing research suggests that medium-sized cities could serve as optimal testing grounds for innovative freight solutions due to their manageable delivery distances, stakeholder engagement potential, and evolving urban logistics strategies. However, the main challenge comes from the fact there is a wide variety of types of medium-sized cities and not all of them can be conductive to the implementation of a cargo bike delivery initiative.

Assessing the feasibility of cargo-bike deployment in medium-sized cities requires a method that accounts for multiple variables, including city size, land-use distribution, cycling infrastructure, and the unique characteristics of each urban area. Given these complexities, this study proposes an approach that evaluates potential deployment by combining two key analytical perspectives: a ranking method that identifies opportunity levels and a cluster analysis that contextualizes these opportunities within each city's specific urban and logistics characteristics. By integrating these dimensions, the study establishes a framework to systematically determine the suitability of cargo-bike logistics across different medium-sized urban settings. Moreover, there is a need to identify cities that share a certain level of homogeneity in their caracteristics with larger cities which already operate with cargo bikes. This is to ensure that the results can be extended with a greater level of confidence.

To address this challenge, this study investigates the following research questions:

- Which key urban and logistical factors influence the suitability of medium-sized cities for cargo-bike deliveries, and how does expert-weighted criteria refinement contribute to this assessment?
- How can the characteristics of identified city clusters guide the formulation of targeted strategies and policies for cargo-bike deployment?

Therefore, this study develops a methodology to assess the potential for cargo-bike deliveries in medium-sized cities using open data and a multi-criteria framework. While the framework is designed for broad applicability, its development and validation are anchored in a case study of medium-sized cities in Quebec. This case serve as an illustratrive example to design the methodological components before generalizing them to a wider context. The approach integrates spatial analysis of population density, land use, cycling infrastructure, and climate data to identify cities best suited for cargo-bike logistics. A hierarchical clustering method, combined to a scenario-based assessment of the potential for cargo bike deployment, is employed to categorize cities based on key urban and logistics characteristics. An expert-driven Delphi survey refines the weighting of assessment criteria. Additionally, the study proposes a ranking system to prioritize cities for pilot implementation based on their suitability for cargo-bike delivery initiatives.

To explore this potential, the following sections of this paper provide a structured analysis. Section 6.3 presents a comprehensive literature review, highlighting the characteristics of medium-sized cities, the benefits and limitations of cargo-bike logistics, and the key factors influencing their adoption. Section 6.4 details the methodology developed to assess the feasibility of cargo-bike deliveries for medium-sized cities, integrating spatial analysis, clustering techniques, and expert input through a Delphi survey. Section 6.5 presents the results of the clustering and ranking analysis, offering insights into the cities best suited for cargo-bike deployment. The results are based on the numerical analyses performed on a sample of medium-sized cities from province of Quebec. Finally, Section 6.6 discusses the implications of the findings, methodological limitations, and avenues for future research in sustainable urban logistics.

6.3 Literature review

This paper presents a comprehensive literature review on the use of cargo bikes for freight delivery in medium-sized cities, a topic of growing interest within urban logistics and sustainable

transportation. However, there are critical limitations to their widespread adoption, including limited cargo capacity, infrastructure demands, and weather-related performance issues. This literature review synthesizes findings on these operational challenges and contextualizes the viability of cargo bike implementation within the unique environment of medium-sized cities, highlighting areas for future research and policy development in sustainable urban logistics.

6.3.1 Freight deliveries in medium-sized cities

The most common characteristic used to define a medium sized city is the population size. Statistics Canada defines a medium population center between 30,000 to 99,999 inhabitants (Statistics Canada, 2017), whereas in France, medium sized cities have a population between 20,000 to 100,000 inhabitants (Demazière, 2014). However, this metric only gives partial representation of what a medium sized city is. Population density, when coupled to population size indicates the distinction between rural and urban land use (Rochefort et al., 2023). Medium sized towns are also characterized by their transportation accessibility, with access to major roads, such as highways and interurban transportation services, which become an indicator of the economic development of this type of cities (Wagner & Growe, 2021). Medium sized cities can also have administrative capacities, with local governments and administrative duties (Servillo et al., 2017). Depending on their distance to major cities, medium-sized towns can either be satellite cities or play a bigger economic role (Rochefort et al., 2023).

Medium-sized cities also come with unique challenges and opportunities when it comes to freight transportation. Overall, there is not enough strategic inclusion of urban freight transportation within the development of medium-sized cities (Flora et al., 2019). However, cities with lower economic growth rates are interested in developing city logistics measures, as it helps to improve the efficiency of the system (De Marco et al., 2018). Overall, distances to cover in medium-sized cities are shorter (Delaitre et al., 2009). Moreover, due to the social organization of medium-sized cities, freight flows are easily identified and improvements can be made with an active participation of concerned stakeholders (Delaitre et al., 2009). As a result, medium-sized towns can become valid testing grounds for urban logistics projects. Therefore, the use of cargo bikes for freight deliveries can represent an interesting opportunity for medium-sized cities. However, certain geographical contexts present unique challenges. In the context of this study, particular attention is paid to winter conditions, such as snowfalls, precipitations, negative temperatures, which can have an important

impact on the feasability of cargo bike delivery initiatives. These constraints are considered within the methodological framework.

6.3.2 Cargo bikes as a sustainable solution for freight deliveries in medium sized cities

An increasing number of studies explore the use of cargo bikes for freight deliveries, highlighting their potential for both environmental and economic benefits, as well as operational advantages. Cyclologistics is defined as the commercial activity of freight transport with bikes and especially cargo bikes, which can handle bigger and heavier loads of freight. Gruber & Narayanan (2019) divide the different types of cargo bikes into five categories: (i) delivery bike, (ii) long tail cargo bike, (iii) long john cargo bike (iii) front load tricycle, (iv) heavy load tricycle. Electric cargo bikes can have an electric assist up to 45 km/h (Narayanan & Antoniou, 2022a), depending on the local regulations.

The use of cargo bikes to transport freight is often associated with positive environmental impacts, especially in urban context for which pollution and congestion represent significant concerns. Positive environmental impacts include air emissions, reduced noise levels, decreased congestion and overall better use of the public space. The life cycle analysis carried by Temporelli et al. (2022) reveals that the replacement of a diesel van by an e-cargo bike yields a reduction of 250 g CO_2 eq / km, in the context of Italy. In their literature review, Vasiutina et al. (2021) examines the different techniques used to assess the environmental impacts of using cargo bikes. Most environmental evaluations are performed on simulated transport systems which include the use of cargo bikes and real-world observations represent only 16 % of their sample. The results of their literature review show that that the lack of uniformity in environmental indicators used make any kind of comparison arduous.

When used in dense urban areas, cargo-bikes can be more cost-efficient than traditional modes of transport for freight. In Seattle (United-States), Sheth et al. (2019) report that cargo bikes are more cost effective when deliveries happen near the consolidation center and when there is a high level of residential units for a lower amount of delivery volume. Cargo bikes can be also competitive in congested areas, which in turns reduces costs by improving efficiency (Conway et al., 2017a).When these factors are considered collectively, cargo bikes present a cost-effective

alternative in urban freight, significantly enhancing logistical efficiency and reducing overhead expenses associated with conventional motorised transport (Nocerino et al., 2016).

Cargo bikes have several operational advantages. One of them is their accessibility to restricted areas, such as low emissions zones or even pedestrian areas (Conway et al., 2017a; Narayanan et al., 2022). Compared to traditional delivery modes, cargo bikes are highly maneuverable and can become real assets in highly congested cities. In Brussels, due to high levels of congestion, cargo bikes travel 42 % faster than delivery vans (16 km/h vs 11.3 km/h) (Kale Ai, 2023). This could be further emphasized by proper optimization of traffic signals on cycling corridors (Jafari et al., 2025).Moreover, from the same study, cargo bikes can park closer to the delivery point (around 35 seconds from the door for cargo bikes, to 5 minutes for vans). These results are consistent with the findings from Dalla Chiara et al. (2023) who find that cargo bikes park around 30 meters from the point of delivery on average. Again, compared to delivery vans, cargo bikes have a small footprint, which make them efficient when kerbspace competition is fierce (M. Sheth et al., 2019). In dense urban areas, cargo bikes are proved to be more competitive than vans, whether in speed of delivery or expenses (Conway et al., 2017a; M. Sheth et al., 2019).

6.3.3 Challenges and limitations to the use of cargo bikes in medium sized cities

To capitalise on the full potential of the use of cargo bikes for freight deliveries, there needs to be specialised infrastructures, such as urban consolidation centers. Most of the urban consolidation centers listed in Katsela et al. (2022) cover large European (Paris, Brussels, London) or North-American (Toronto, Montreal, Seattle, Miami) cities. Medium-sized cities do not have the financial capacity or needs to establish local urban consolidation centers, even though they are required for cargo bikes (Rudolph et al., 2021). Specialised infrastructures also include routes that can accommodate for their size and weight (G. Liu et al., 2020), an interconnected bike lane network (Dalla Chiara et al., 2023) and spaces to park (Carracedo & Mostofi, 2022; Dalla Chiara et al., 2023).

Even if cargo bikes are highly competitive in dense urban areas, their load capacity and distances can become a concern. Cargo bike capacities as well as reported speeds in the literature vary greatly according to the geographical context and type of bike used to perform the delivery. Trikes, used in Gruber & Narayanan (2019) and Sheth et al. (2019), have greater capacities (over 200 kgs) than cargo bikes used in Assmann et al. (2020), Büttgen et al. (2021), Fraselle et al. (2021), Gonzalez-

Calderon et al. (2022), Hofmann et al. (2017), Koning & Conway (2016), Narayanan et al. (2022), Nocerino et al. (2016), Robichet et al. (2022) which can carry between 120 – 200 kg of goods. Regular bikes with either very small trailers or backpacks. Gonzalez-Calderon et al. (2022) and Nocerino et al. (2016) have the smallest capacity around 15-25 kgs.

Distances covered by cargo bikes can be quite short, in Montreal (Canada), cargo bikes are used to cover approximatively a radius of 3 km from the depot (Pirie et al., 2024). Cargo bikes are most cost efficient than delivery trucks for routes under 10 km (6 miles) in Seattle (United-States) (M. Sheth et al., 2019). In their study, Robichet et al. (2022) use a 2 km radius from the depot for cargo bikes use in Paris (France). Therefore, in medium sized cities, in which population density can be lower and urban sprawl more present, this could be a challenge for cargo bikes initiatives.

Even though cargo bikes can be highly competitive, several factors can impact their performance as well as the well-being of cargo bike drivers. For example, studies on winter conditions such as extreme cold weather, snowfalls, ice on the roads etc. on the use of commercial cargo bikes are scarce. Dybdalen & Ryeng (2022) study the use of cargo bikes in several Norwegian cities and how winter conditions, such as low temperatures, snow on the road, and snowfalls, are handled. They conclude that the design of the bike itself (stronger braking system, bigger wheels, easy maintenance) is important to ensure winter operations. Work organisation must also be revised to allow proper breaks in a warm environment for employees and proper cycling infrastructures ensure better safety for winter commercial bikers. Giordano et al. (2022) show that temperatures can influence the performance of cargo bikes' batteries. The same study also shows the presence of snow and or slush (mix of snow and water) on the road could increase the riders' energy-use by 2.8 to 16.4% (Giordano et al., 2022). Malik et al. (2023) consider rainfall and temperatures as parameters for a study on the factors influencing cargo bike purchases for businesses in Ireland. The results of the study indicate that the combined effects of rain and daily temperature are significant factors that influence the purchase of cargo bikes (Malik et al., 2023).

In conclusion, the existing body of research highlights the environmental and operational advantages of cargo bikes for last-mile logistics, particularly in densely populated urban centers. However, the majority of studies focus on large metropolitan areas, leaving a significant research gap concerning their feasibility in medium-sized cities. Despite indications that medium-sized cities could serve as promising environments for cargo-bike implementation—due to manageable

delivery distances, stakeholder engagement potential, and evolving urban logistics strategies—there remains a lack of a standardized method to assess their viability in such contexts.

Current assessments of cargo-bike potential rely heavily on case studies, simulation-based models, or qualitative analyses, often overlooking the spatial, infrastructural, and logistical specificities of medium-sized cities. Additionally, while previous studies identify critical operational challenges—such as cargo capacity limitations, infrastructure requirements, and climatic constraints—there is no established framework to systematically evaluate their impact on cargo-bike deployment at an intermediate urban scale.

To address this gap, this study introduces a novel methodology leveraging open data and a multi-criteria assessment framework to systematically evaluate the potential of medium-sized cities for cargo-bike logistics. By integrating spatial clustering techniques, scenario-based evaluations, and expert-driven weighting mechanisms, the proposed methodological contribution enables a more comprehensive and scalable assessment of cargo-bike suitability.

6.4 Methodology

6.4.1 Research design

The nature of this study is exploratory and aims to include and merge qualitative and quantitative data sources to establish the potential for medium-sized towns that are conductive to implementing cargo bike delivery initiatives. The potential is derived from the ranking of each medium-sized city to identify high-priority candidates for cargo-bike deployment. This is complemented by a cluster analysis, which contextualizes the ranking results by grouping cities with similar urban and logistical characteristics. Together, these methods enable a strategic, scalable approach to cargo-bike implementation tailored to the specific needs of different urban contexts.

One of the main aspects of this study is that it is based exclusively on open-source data and open-source tools to perform the data treatment. The expert-driven Delphi survey refines the weighting of assessment criteria by integrating perspectives from two key stakeholder groups: (1) experts in cargo-bike logistics, who provide operational insights, and (2) experts in cycling infrastructure, who assess the feasibility of urban integration. Their collective input ensures that the ranking and clustering methods are grounded in real-world implementation constraints. The methodology developed to establish the potential of use of cargo bikes within a medium sized city is motivated

from the lack of initiatives for such cities and the tendency to only consider large cities as suitable playing grounds for innovative freight transportation (Flora et al., 2019). The main framework for the methodology is adapted from Rochefort et al. (2023), whose study is meant to better apprehend the differences between small and medium sized cities. As their methodology is based on public data, it is possible to adapt it for the specific needs for cargo bike delivery initiatives. To achieve this, this study includes a qualitative survey to properly weight the criteria used.

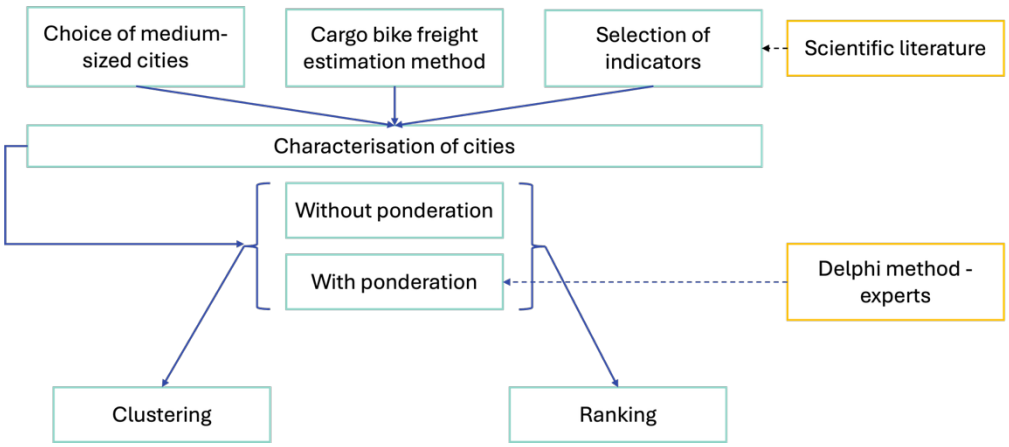


Figure 6.1 General methodology

The methodology is structured as follows: first, we define the selection criteria and data sources; second, we present the ranking system and clustering method used to classify cities; third, we outline the Delphi method for expert input; and finally, we discuss the validation process and scalability of the framework for the scenarios in the freight estimation method (**Erreur! Source du renvoi introuvable.**).

6.4.2 Selection of medium-sized cities

Depending on the geographical context considered, medium sized cities may differ in size and characteristics. The United Nations consider a medium city to be between 50,000 and 500,000 inhabitants (United Nations, 2020). In Quebec, the thresholds to establish the size of a city range from 100,000 inhabitants and more, 25,000 to 99,999 inhabitants, 10,000 to 24,999 inhabitants, 2,000 to 9,999 inhabitants and less than 2,000 inhabitants (*Ministère des Affaires municipales et*

de l'Habitation). For the context of this study and in order to define what a medium study is for reproducibility purposes, we study the distribution of city population for the province of Quebec based on the 2021 census (Table 6.1). The provinces of Ontario and Saskatchewan (Canada) are also studied to provide global context.

Table 6.1 Distribution of population amongst Quebec, Ontario and Saskatchewan (Canada)

	Number of municipalities	Min	Mean	25 %	50 %	75 %	Max
Quebec	1,274	0	6,673	453	1,056	2,614	1,762,949
Ontario	564	0	25,219	530	2,827	10,910	2,794,356
Saskatchewan	950	0	1,193	116	304	613	266,141

Based on the distribution of the Quebec population, the thresholds established by the Ministry of Municipal Affairs and Housing and the UN criteria, the size of medium towns for this study is a population size comprised between 25,000 and under 500,000 inhabitants. A threshold of 25,000 inhabitants represents the 96th percentile in the population distribution of Quebec, with 51

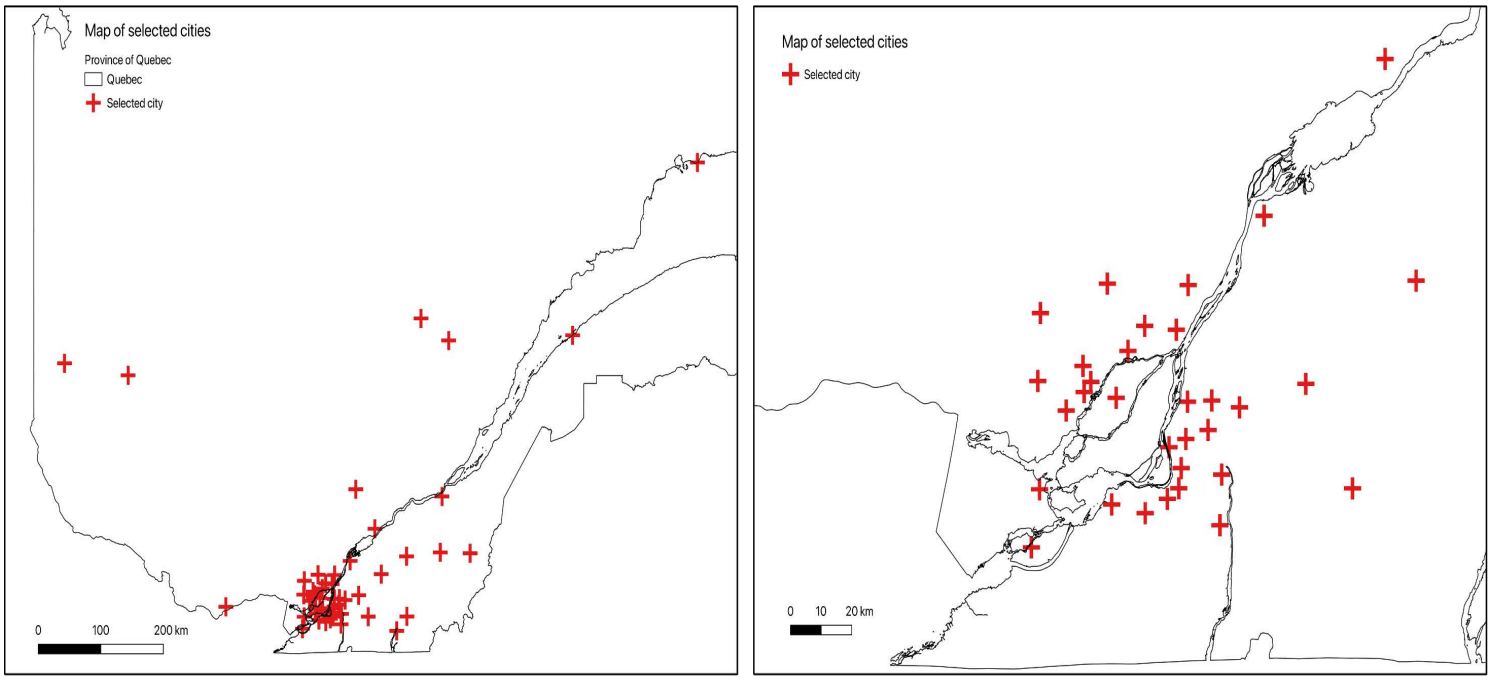


Figure 6.2 Maps of the 46 selected cities, at the provincial level (left) and Greater Montreal level (right)

municipalities over this threshold. When withdrawing the two cities with population over 500,000, 49 cities are now considered for the scope of this study. Within these 49 cities, three are locally based on the Island of Montreal but are their own administrative entities. These three cities are withdrawn from the sample of medium-sized cities because their location is within the primary zone of influence of Montreal. This decision ensures that the selected cities are not directly influenced by the policies and economic conditions directed by the city of Montreal. The goal of the selection process of the medium-sized cities is to strike a balance between cities which share a certain level of homogeineity through their size with larger cities like Montreal and Quebec city, and a level of independence to identify which caracteristics make them conductive to having cargo bikes for deliveries. A total of 46 cities are selected (Figure 6.2).

6.4.3 Criteria and data acquisition

This subsection aims at presenting the preliminary pool of criteria which can be considered to evaluate the potential of cities to receive cargo bike initiatives. The criteria are divided in several categories: population data, flows, zoning, geography and infrastructures (Table 6.2).

Table 6.2 Criteria and indicators considered by category

Category	Criteria	Indicator(s)
Population data	Population density*	Number of inhabitants per km^2
	City population	Total city population
	Population compactness*	Indicator of the population compactness
	Population evolution rate*	Difference between the 2021 and 2016 census (%)
Zoning	Zoning regulations	Proportion of residential zoning (%)
		Proportion of manufacturing zoning (%)
		Proportion of commercial zoning (%)
		Proportion of transport zoning (%)
		Proportion of services zoning (%)
		Proportion of cultural and recreational zoning (%)
		Proportion of production and extraction of natural resources zoning (%)
		Non-operated buildings and bodies of water zoning (%)
Geography	Topography	Mean elevation (m)
		Max elevation (m)
		Min elevation (m)
		Delta elevation (m)
	Weather conditions	Average temperature (degrees Celsius)
		Mean of daily minimum temperature in degrees Celsius
		Mean of daily maximum temperature in degrees Celsius
		Number of days under negative 15 degrees Celsius
		Total amount of precipitations (in mm)
Infrastructures	Cycle networks	Proportion of high-comfort bikeways (%)
		Proportion of medium-comfort bikeways (%)
		Proportion of low-comfort bikeways (%)
		Proportion of non-conforming bikeways (%)
		Diversity score of bikeways
		Quality score of bikeways

Some of the criteria and relative indicators are adapted and inspired by Rochefort et al. (2023), who developed a method to classify Quebec's towns to better consider their differences based on a multicriteria method. All criteria based on their work are indicated in Table 6.2 with an *

afterwards. Criteria which are more relevant to cargo bike deliveries are added by the authors, particularly topography, weather conditions, cycling networks etc. The population density is calculated by dividing the total number of inhabitants by the area of the municipality, based on the 2021 Canadian census.

As mentioned in Rochefort et al. (2023), several towns in the province of Quebec cover important superficies, enven though their inhabitants live nearer the city centers. To better factor this reality within the data for this study, a compactness indicator is calculated for each city.

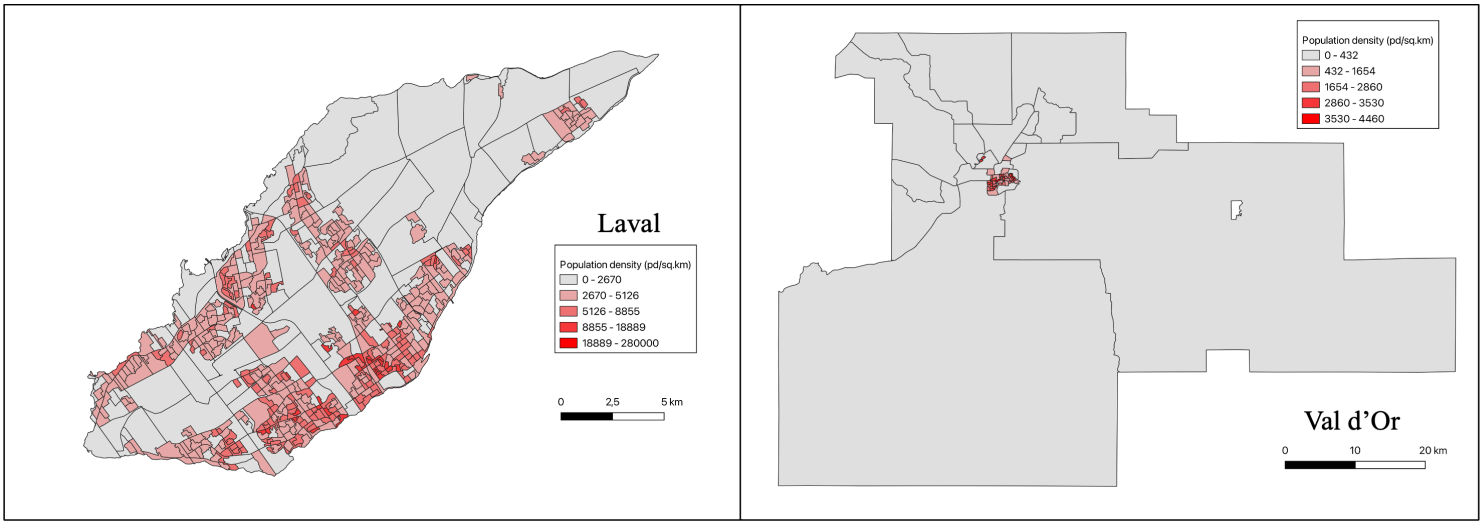


Figure 6.3 Examples of compactness indicators for the cities of Laval and Val d'Or

For each municipality, the total area is calculated for which the population density is higher than the first quartile of the population density distribution for the municipality. Then, the compactness indicator is measured by dividing the area of denser population by the total area of the municipality. The city with the lowest compactness is Val d'Or (0.14) and the city with the highest compactness indicator is Laval (0.33) (Figure 6.3). The evolution rate of the population is the difference between the population from the 2021 Canadian census and the 2016 Canadian census for each municipality. The zoning data comes from the Government of Quebec land use data. Each unit is coded to represent the main land use. The codification of land use allows for quick and easy categorization, as represented in Table 6.3. CUBF_2 includes industries which specialize on processing raw or

primary materials, whereas CUBF_3 covers more specialized and advanced manufacturing sectors. Detailed profiles of land use for the selected cities can be found in Table A.1.

Table 6.3 Land use categories for the province of Quebec (Canada)

Land use code (CUBF_X)	Name of category	Example(s)
CUBF_1	Residential	1000 – House, appartement
		1600 – Hotel
CUBF_2	Manufacturing industries	2913 - Newsprint and groundwood printing paper industry
CUBF_3	Manufacturing industries	3840 - Pharmaceutical products and medicines industry
CUBF_4	Transport, communications and utilities	4222- Garage and maintenance equipment for truck transport (including municipal garages)
CUBF_5	Commercial	5411- Grocery retailing with butchery
		5260 - Retail sale of women's ready-to-wear clothing
CUBF_6	Services	600 – Office building
		6812 – Elementary school
CUBF_7	Cultural, recreational and leisure activities	761- Park
		7233- Meeting rooms, conference centre
CUBF_8	Production and extraction of natural resources	813- Crop production
CUBF_9	Non-operated buildings and bodies of water	931- River and stream
		934- Sea and ocean

Topography can play an important role in the success or demise of cargo bike utilization. For each considered municipality, we use the hypsometric data provided by the government of Quebec. The hypsometric data contains elevation lines, from which we can calculate the maximum elevation, minimum elevation, and the average elevation over each territory of the municipality. From this collected data, the difference (delta elevation) is calculated between the maximum and minimum elevation points in order to establish the hilliness of each selected city.

Considering the climatic conditions experiences in Quebec, several criteria are considered to properly integrate the weather conditions. All weather data comes from the climate data platform,

which provides detailed variables based on historical data as well as projected data (Données Climatiques Canada, 2024). The data is based on the corrected data developed by the government of Canada. The timeframe chosen for the weather data is from 2018 to 2023 for historical data and 2024 to 2029 for projected data. As cargo bikes delivery initiative are mostly forecasted, the use of projected weather data helps to correctly account for future climate evolution. Weather indicators which are chosen to represent the conditions in all seasons include: the average temperature over the timeframe period, the mean of daily minimum temperatures, the mean of the maximum daily temperature, the number of days under negative 15 degrees, and the total amount of precipitations.

As the focus of this study is on cargo bikes, several indicators cover different aspects of the cycle network. The data for the cycle network comes from the Can-BICS dataset (Winters et al., 2020). The Can-BICS dataset is based on open street map (OSM) data and classifies the cycle network into three main categories: (i) high-comfort bikeways, (ii) medium-comfort bikeways and (iii) low-comfort bikeways (Winters et al., 2020). High-comfort bikeways are defined as low-stress routes comfortable for most people, including those of all ages and abilities, such as physically separated roadway lanes. Medium-comfort bikeways are defined as low to medium-stress routes comfortable for some people, but whose safety require careful design, such as multi-use paths that can be shared between cyclists and pedestrians. Low-comfort bikeways are high-stress routes comfortable for few people, with little or no additional safety compared to no bicycle facility, such as painted bike lanes. A last category exists in the Can-BICS dataset, which is “non-conforming”. This means that the bikeways do not meet the minimum standard, such as trails or unpaved surfaces. From this dataset, it is possible to determine the proportion of each level of comfort for each municipality. From this data, a diversity score of bikeways for each city is calculated, using the Shannon’s entropy and a quality score of bikeways is also calculated, by attributing higher marks for high level of comfort to lower marks for non-conforming. These two calculated indicators help to reflect the real infrastructure conditions for each city.

6.4.4 Freight potential estimation method

This subsection presents the methodology to estimate the freight potential without the use of private freight data.

The government of Quebec offers an open-source inventory of all the buildings located within a municipality, assessed on the same basis and on the same date. The dataset used for this study is

from 2023. It contains the area for each building as well as the code that best describes the predominant use that is made of the building. From this codification, it is possible to calculate the proportion of each use (i.e. commercial, residential, services etc.). Then, each municipality is divided into smaller hexagons to establish the profile of each hexagon. The grid size for each hexagon is 500 x 500 m, with a surface area of ~0.22 km^2. The hexagons are then coupled with the land use dataset to establish the profiles of each hexagon (Figure 6.5).

To establish the profile of each hexagon, the number of units for each land use code is compiled, along with the total area (in m^2). For each hexagon, the dominant land use is established based on the total area (in m^2) occupied by the land use. Within the nine categories of land use, only four categories are considered: residential, commercial, services and cultural/leisure. The hexagons with a dominant land use code from the commercial, services and cultural/leisure categories are considered as freight emitting hexagons, whereas the hexagons with a dominant residential land use code are considered as freight receiving hexagons. In this article, the hypothesis relies on local deliveries made either from businesses to other businesses (B2B) or from businesses to nearby consumers (B2C), reflecting the types of trips typically performed using cargo bikes in urban settings.

For each hexagon, the Shannon's entropy is calculated to assess for the diversity of land use codes. Shannon's entropy considers both the number of land use categories and their distribution within the hexagon. A perfectly even distribution will have a higher entropy, whereas a hexagon dominated by only one land use code will have a lower entropy.

$$H = -\sum_{i=1}^{n} p_i \log(p_i)$$

Where:

$-\ p_i$ is the proportion of land use category i within a hexagon (i.e., the percentage contribution of that land use to the total area of the hexagon).

$-\ n$ is the number of unique land use categories within the hexagon.

While Shannon's entropy is a useful proxy for estimating land use diversity, it does not account for the spatial arrangement of those uses within the hexagon, which may also affect delivery feasibility and infrastructure needs.

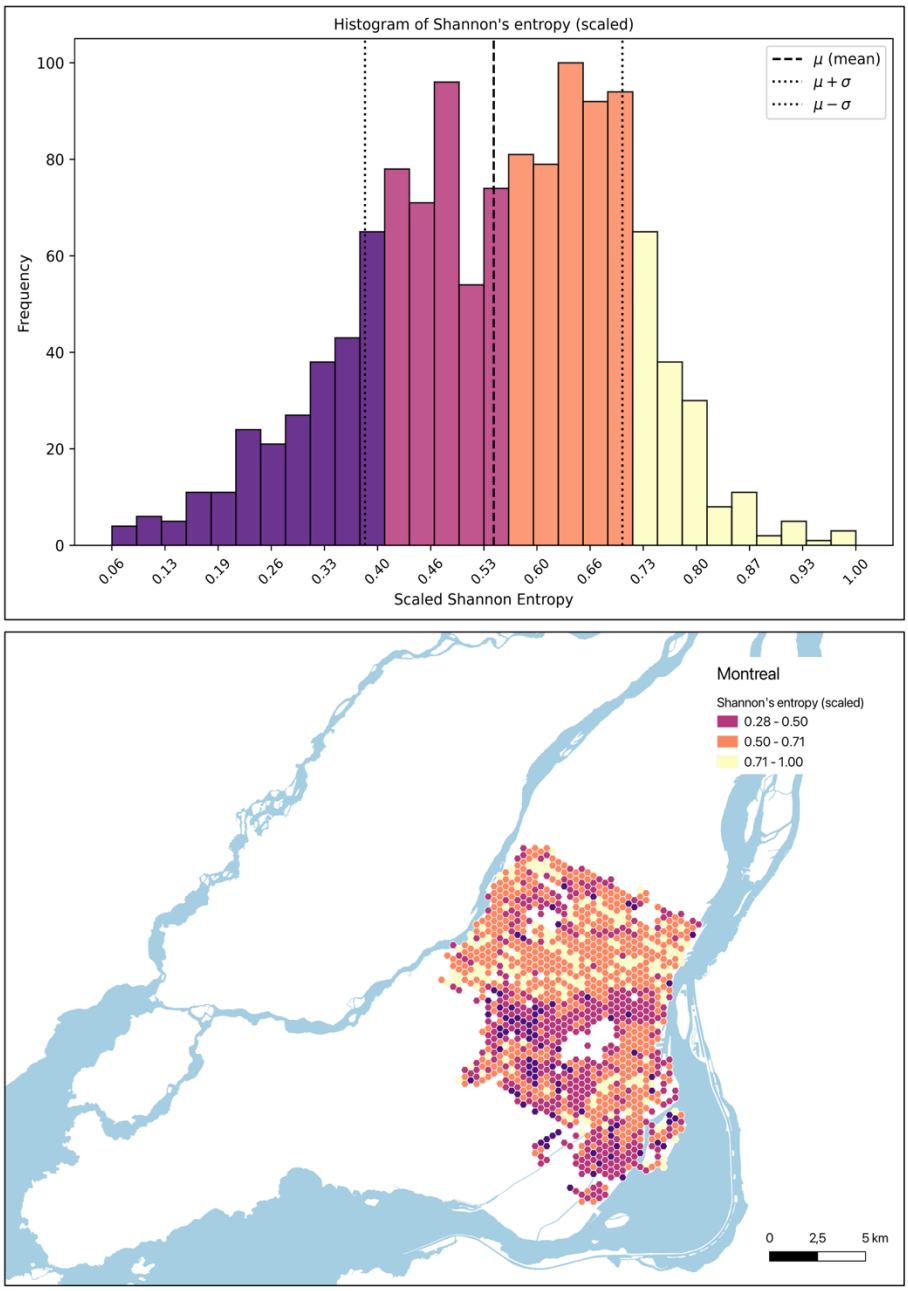


Figure 6.4 Distribution of Shannon's entropy (left) for Montreal (right)

To determine whether the use of cargo bikes for goods delivery would be relevant for medium-sized cities, scenarios are developed based on the data for the city of Montreal, which currently has several companies which operate with cargo bikes. To prepare the different scenarios, the same methodology is applied to establish the profile of the hexagon based on the territory covered by cargo bike riders in Montreal (Figure 6.4).

Based on the dominant land use for each hexagon and its relative Shannon's entropy, it is possible to establish three scenarios which will act as filters in the rest of the methodology (Table 6.4). Scenario 1 represents a short-term implementation of cargo bike deliveries. In this scenario, the Shannon's entropy is high (> 0.71), which means that the hexagons present a high diversity of usage behind the dominant land use code. The radius of action chosen for the cargo bikes is based on previous work done in Montreal (see Pirie et al. (2024)), and is a radius of 3 kilometers. In the future, this radius could be increased based on the technological advances of cargo-bikes. In Scenario A, the threshold for the entropy to capitalize on smaller covered regions but with a higher chance of success. This scenario would also require less cargo-bikes to run and therefore be interesting to perform pilot projects in medium-sized cities. Scenario B is the logical continuity of Scenario A, in which the threshold for the Shannon's entropy is relaxed to >0.50 (medium-high value). This scenario represents a medium-term implantation ("ramping-up"), which would require potentially more than one cargo-bike to cover the area selected but which limits the potential for the delivery initiative to fail. Scenario C is the long-term implementation ("scaling-up"), for which the threshold for the Shannon's entropy is low (>0.28), meaning that the area covered will include hexagons for which the diversity of land use is lower. This scenario represents the long-term implementation, with several cargo bikes used to cover the area. For all scenarios, only hexagons located in areas where the population density is greater than 25% are selected.

Table 6.4 Synthesis of scenarios applied to medium-sized cities

	Scenario A Pilot project	Scenario B Ramping-up	Scenario C Scaling-up
Shannon's entropy (scaled)	> 0.71	> 0.50	> 0.28
Radius of action (km)	3	3	3
Density of population	> 25 %	> 25 %	>25%

Back to the dataset for the medium-sized cities, a filtering process based on the scenarios developed is applied to the set of hexagons. Only hexagons corresponding to land use codes residential (CUBF_1), commercial (CUBF_5), services (CUBF_6), recreational/leisure (CUBF_7) are selected. For each hexagon, the centroid is calculated, then from hexagons with dominant land use code equal to 5,6 and 7, a 3 km radius is calculated. Then, within the 3 km radius, hexagons which are selected are continuous from the hexagon of freight emission (land use code 5, 6 or 7), or with only one hexagon apart. Selected hexagons must also have a Shannon's entropy superior to the threshold of the scenario considered. Each group of hexagons represents a cluster, with a unique id. This clustering approach is exploratory in nature and was not subject to formal validation; its purpose is to identify emerging spatial patterns that may inform further, more robust analyses, in future research.

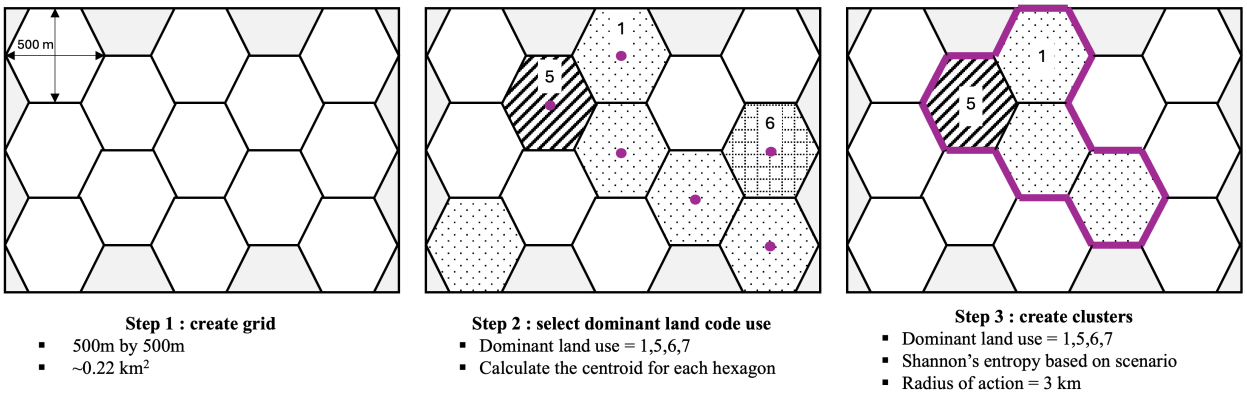


Figure 6.5 Land use by hexagon method for freight potential

The results for the scenarios previously obtained have been further validated through their application to an additional region within the city of Quebec. This region has recently been identified as a target for expansion by the current cargo bike delivery service. The findings demonstrate a strong alignment with the initial results, as demonstrated with the distribution of the entropy (scaled) for Quebec City (Figure 6.6).

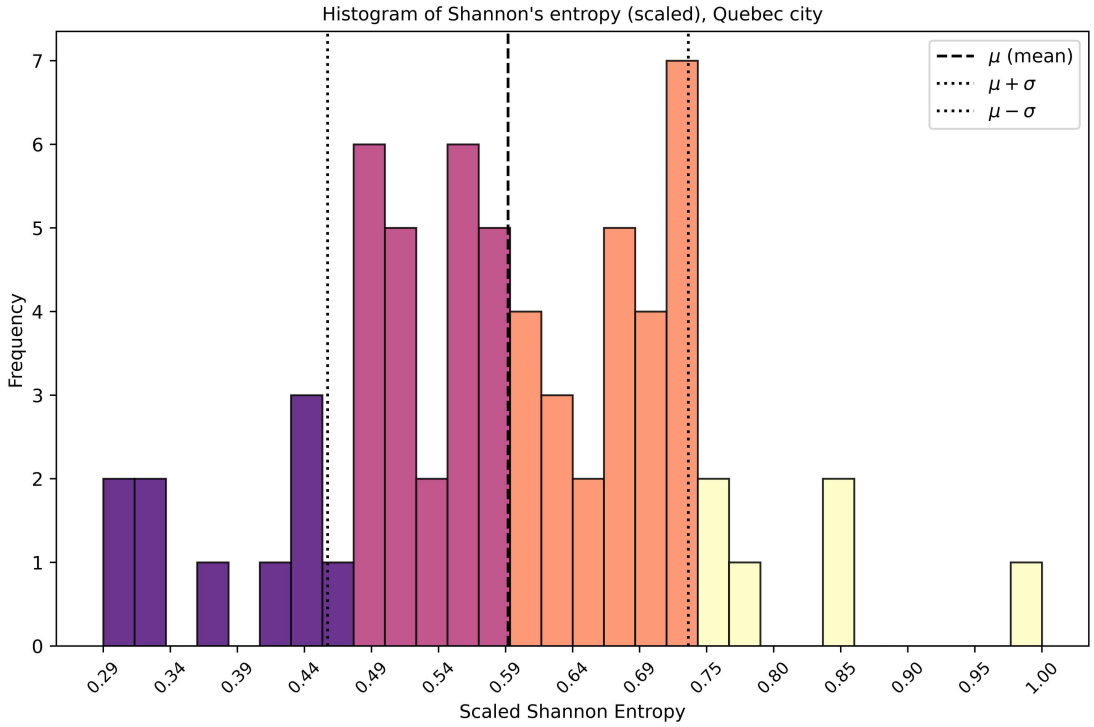


Figure 6.6 Histogram of Shannon's entropy (scaled) for the city of Quebec (Canada)

6.4.5 Delphi method for criteria weighting

In order to weight the various criteria presented in Section 6.4.3 correctly, a Delphi method is introduced. In total, twelve individuals with different areas of expertise answered a short survey. These individuals are divided into two groups, “experts in cyclologistics” and “cycling infrastructure experts” (Table 6.5). The first group has a strong expertise when it comes to cargo bikes for freight deliveries. The second group works closely with and within the ecosystem of cycling, from urbanists, mobility consultants to university professors. For both groups, 6 people were questioned and experts could only participate in one group.

Table 6.5 Distribution of experts by group and profession

Group A		Group B	
Experts in cyclologistics	n= 6	Experts in bike infrastructure	n= 6
Mobility consultant	2	Public health analysist	1
Academic	2	Municipal leader	1
Municipal leader	1	Mobility consultant	3
Freight carrier	1	Academic	1

When asked about their personal knowledge on cyclologistics from 0 to 10 (ten being an absolute expert), group A reported to be at 8/10 on average, whereas group B reported to be at 4.5/10 on average. Overall, group B had heard about cargo bike deliveries in general from public media coverage or word of mouth.

These two groups were asked the same questions (see Annexe A), formulated as a statement to which the respondents chose the level to which they agreed. This method provides a score out of 5 for each question and each respondent for each item scored. The results of the questionnaire for each group are presented in subection 6.5.2 of this paper. Based on the results of the survey, a weighted score is calculated by dividing the average score by the maximum possible score. Results are presented in Table 6.6.

Table 6.6 Weight by criterion

Criterion	Weighted Score
Population density (inhabitants/km²)	1.00
Population growth rate (2016-2021)	0.50
City elevation changes – topography	0.85
Climatic conditions (precipitation, average temperatures, etc.)	0.65
Zoning (commercial, residential, etc.)	0.85
Quality of cycling infrastructure	0.75
Diversity of cycling infrastructure	0.75

6.4.6 Clustering method

A hierarchical ascending classification (HAC) approach was employed to group cities based on their internal similarity while maximizing differentiation between groups. The Ward's minimum variance method was used, which minimizes intra-group variance at each step to ensure compact and distinct clusters. This method offers a key advantage over K-means clustering, as it does not require a predefined number of clusters, allowing for a more data-driven classification, as mentioned in Rochefort et al. (2023). The hierarchical clustering was implemented using the hclust function in R (R Core Team, 2021), providing a robust framework for identifying structurally meaningful groups within the dataset. The considered indicators include total population, population density, population growth rate, city compactness index, altitude variation, number of days below -15°C, and average annual precipitation. Additionally, cycling infrastructure quality was assessed using a diversity score of comfort levels and a quality score of cycling lanes. The diversity of land use was quantified through Shannon entropy at the city scale. Finally, the number of hexagons selected under Scenario A, B and C are added as clustering variables. The number of clusters is provided from the hierarchical clustering by inspecting the inertia jumps from the dendrogram results. In the context of Ward's distance, the inertia jump represents the changes in within-cluster variance at each step of clustering. In the case of this study, an optimal number of 7 clusters is chosen.

6.4.7 Ranking method used

Each city is assigned a rank based on the considered variable, following either a descending or ascending order. For instance, population density is ranked in descending order, with rank 1 assigned to the city with the highest density, whereas the number of days below -15°C is ranked in ascending order, with rank 1 corresponding to the city experiencing the fewest such days. The non-weighted version aggregates the ranks per city, where a lower total score indicates a better ranking. In the weighted version, the same aggregation is performed but incorporates predefined weights, derived from the Delphi method, to reflect the relative importance of each variable. The selected variables and weights align with those used in clustering analyses.

6.5 Results

The numerical analysis conducted focused on medium-sized cities in the province of Quebec, Canada. Through this case study, we illustrate how the proposed methodological framework can be applied to identify the medium-sized cities best suited for cargo bike initiatives. The following results include a portrait of selected hexagons for the cities and the results of the clustering and methods. Cluster profiles are examined in the differences, as well as the final scores for each city to help determine if cargo bikes could represent a possible delivery method in the selected cities.

6.5.1 Eligible hexagons under Scenarios A, B and C

Table 6.7 presents the distribution of hexagons according to the scenario considered. In Scenario A (Entropy > 0.71), only 33 cities (71.74 % of the sample) have at least one selected hexagon that meets the selection criteria. Provided that the criteria considered for the pilot project is strict, the 28.26 % of cities that have zero selected hexagon do not have a high enough entropy per hexagon. The cities which have 0 selected hexagons in Scenario A share a high proportion of dominant residential zoning (60% on average) of their territory. On the contrary, cities which have selected hexagons in Scenario A have lower dominant residential zoning (40 % on average). However, in general for Scenario A, a mean of 3 hexagons is observed, which represents ~0.66 km^2, which is by far inferior to the capacity of a cargo bike. Therefore, cities would probably need only one cargo bike within the pilot project. In Scenarios B and C, all cities are covered by hexagons, which a respective mean of 23 and 104 hexagons. 23 hexagons represent a covered area of 5.06 km^2 and 104 hexagons a covered area of 22.88 km^2. Both areas covered are still inferior to the coverage capacity of a single cargo bike operating from a central micro-hub (~28.27 km^2). Overall, the distribution of the number of hexagons under the different scenarios vary greatly, especially for Scenario C. An example based on the medium-sized city of St-Georges is provided in Figure 6.7

Table 6.7 Distribution of hexagons by Scenario

Scenario	Count	Mean	Std dev
Scenario A	33	3.12	1.41
Scenario B	46	22.61	19.44
Scenario C	46	104.41	94.42

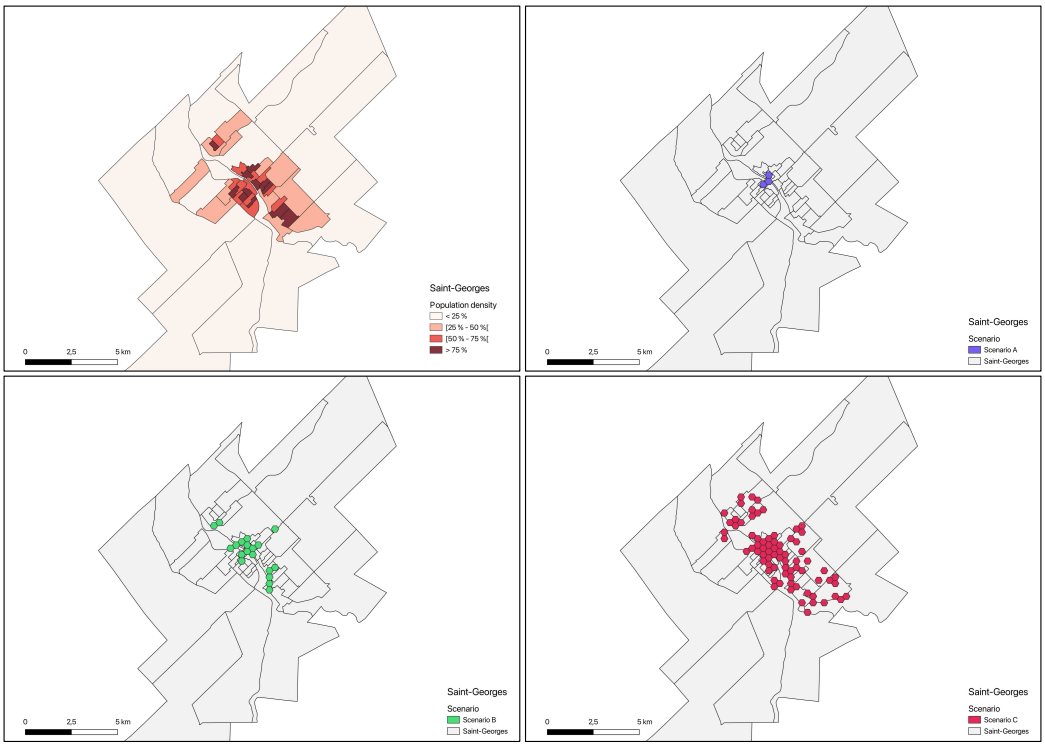


Figure 6.7 Hexagons selected by scenario, for the city of Saint-Georges

6.5.2 Results from the survey

This subsection provides the results of the score from the Delphi method, synthetized in Table 6.8.

Table 6.8 Average scores for each group of experts

Factor	Group A - Cyclologistic experts (avg. score /5)	Group B - Cycling infrastructure experts (avg. score /5)
Population density (inhabitants/km²)	5	3.25
Population growth rate (2016-2021)	2.5	2
City elevation changes – topography	4.25	3.75
Climatic conditions (precipitation, average temperatures, etc.)	3.25	3.75
Population flows	3	3.25
Goods flows	4.25	4.75
Zoning (commercial, residential, etc.)	4.25	3.5
Diversity and quality of cycling infrastructure	3.75	4
Availability of transport data (volumes, origin and destination, etc.)	4	5
Knowledge and/or expertise in urban logistics and/or cyclologistics	3.75	4
Support from professionals with relevant expertise	4	4.5
Knowledge of various funding sources (banks, public financing, ministry grants, etc.)	3	4.25
Accessibility of knowledge on different funding sources	3.25	4

The population density metric received the highest score from cyclologistics experts (5.0) compared to cycling infrastructure experts (3.25), indicating that cyclologistics experts place a higher emphasis on population density in evaluating cycling logistics. The population growth rate was rated similarly low by both groups, with scores of 2.5 and 2.0 respectively, showing a consensus that it is a lesser priority factor. City elevation changes were rated moderately high by both groups, though cyclologistics experts (4.25) showed a slightly greater sensitivity to this factor than infrastructure experts (3.75). Climatic conditions, including precipitation and average temperatures, were viewed similarly by both groups but slightly more critical for infrastructure experts (3.75). Factors related to logistics, such as population and goods flows, received higher scores. Goods flows, in particular, were rated highly by both groups, with infrastructure experts giving it the highest overall rating (4.75). This reflects the importance of understanding the movement of goods in both fields, especially within urban environments. However, this information is the least accessible one, as it is often held by private freight carriers and represents

a strategic element for their business. This result further motivates the need to involve freight carriers that normally deliver these cities as important stakeholders for cargo bike delivery initiatives.

Zoning and the cycling infrastructure were also key considerations. Cyclologistics experts gave slightly higher ratings to zoning (4.25) compared to infrastructure experts (3.5), suggesting a nuanced view on how zoning impacts logistics operations. Conversely, cycling infrastructure experts rated the presence of infrastructure higher (4.0) compared to cyclologistics experts (3.75). This can be explained by the fact that cargo bike riders are considered expert riders and are less sensitive to the quality of infrastructure than a regular rider. However, their safety can be impacted by the lack of infrastructure, which is an aspect that experts in infrastructures often look after. Regarding the availability of transport data, cycling infrastructure experts rated this factor at the maximum score (5.0), showing its high relevance to their work. Similarly, both groups valued knowledge and support from professionals, with infrastructure experts scoring these factors slightly higher (4.5 for professional support and 4.0 for knowledge).

Lastly, factors related to funding knowledge and accessibility showed notable differences. Infrastructure experts placed more importance on both the knowledge (4.25) and accessibility (4.0) of funding sources, compared to lower ratings from cyclologistics experts (3.0 and 3.25, respectively). This difference suggests that infrastructure experts might face more financial considerations in their work.

6.5.3 Hierarchical clustering results

The clustering results are presented in this sub-section, by category of indicator, for weighted and non-weighted clustering based on the results of the Delphi panel. The first part examines cluster stability and the second part cluster fragmentation, identifying key factors that contribute to the reorganization of cities under weighted clustering.

Figure 6.8 presents the maps of the cities by cluster, for both non-weighted and weighted data. The

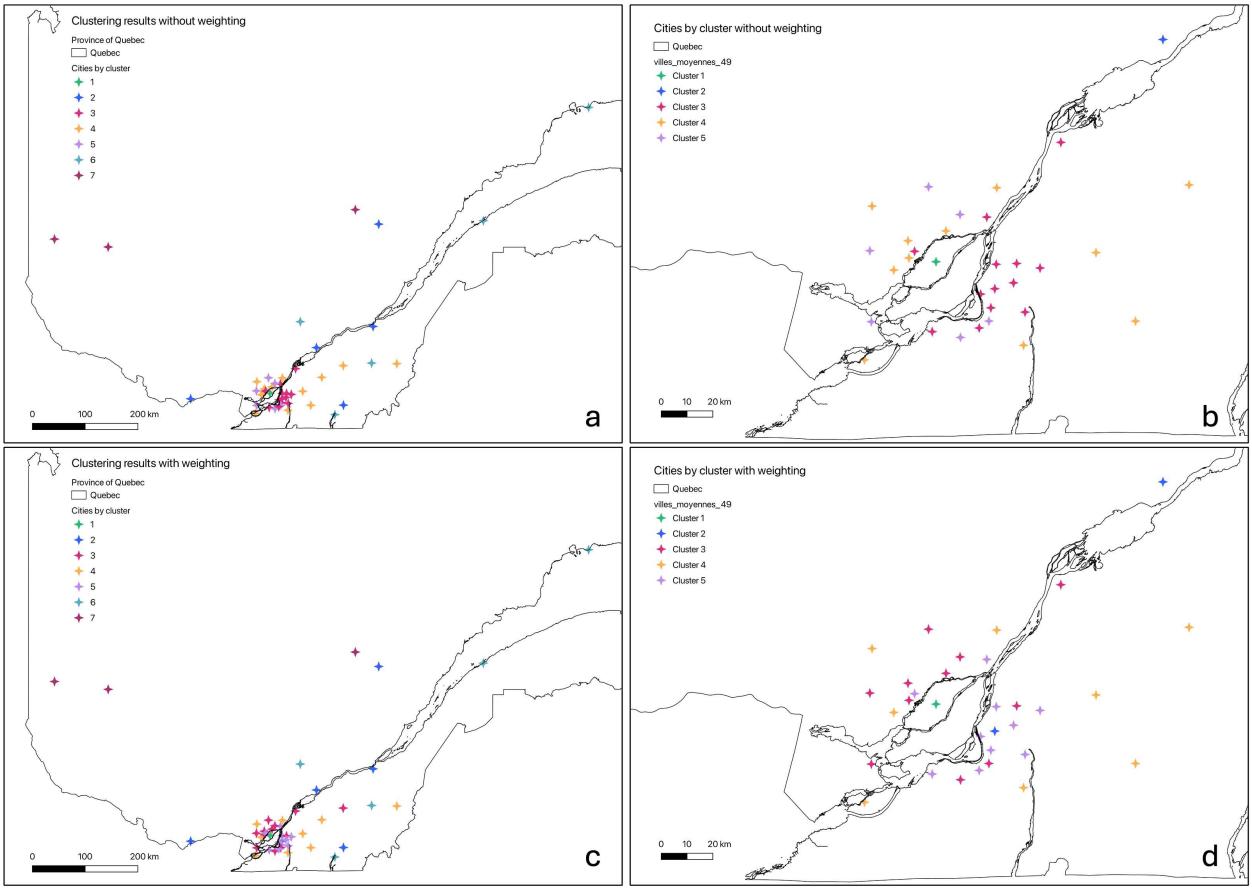


Figure 6.8 Map of clustering results (a) non-weighted at the provincial level and (b) non-weighted at the Greater Montreal level, (c) weighted at the provincial level and (d) weighted at the Greater Montreal level

Adjusted Rand Index (ARI) score is calculated between the two clusters and is equal to 0.6144. The Adjusted Rand Index is a statistical measure to evaluate the similarity between two clustering solutions by quantifying the agreement and adjusted by chance (Yeung et al., 2001). An ARI score ranges from -1 to 1, where a score of 1 indicates perfect agreement, 0 reflects a level of agreement expected by random chance, and negative values suggest less agreement than random assignment.

In the case of the clustering, a score a 0.6144 indicates that the agreement is moderate. The clustering method captures similar underlying structure in the data, but differences between clusters remain present. From the different clusters produced, it is possible to establish cluster typologies, which help to caracterize the medium-sized cities according to how conductive they might be for cargo bike delivery initiatives.

6.5.4 Weighted Cluster typologies

Cluster 1 consists of a single city, Laval, which is characterized by high urbanization, compactness, and well-developed biking infrastructure. The city demonstrates both high diversity and quality of bikelane networks, reinforcing its capacity for sustainable urban mobility. When analyzing scenarios A, B, and C, Laval exhibits the second highest number of eligible hexagons in Scenario A, suggesting that it is an optimal candidate for a pilot project involving cargo bike deliveries. The city's urban characteristics align closely with those of Montreal and Quebec, both of which have successfully implemented cargo bike solutions for urban freight distribution. Additionally, Laval's relatively flat topography and moderate climatic constraints during winter enhance its viability for year-round cargo bike operations. Given these conditions, Cluster 1 presents a strong case for the rapid deployment and long-term scalability of cargo bike delivery systems as a sustainable urban logistics solution.

Cluster 2 comprises some of the largest cities by population from the considered subset, though they exhibit moderate density due to lower compactness levels. These cities are not located in the immediate vicinity of Montreal or Quebec city, indicating a degree of spatial separation from the province's primary urban centers. The urban fabric of Cluster 2 is characterized by moderate zoning diversity and a high rate of population change, suggesting ongoing urban development and potential shifts in land use patterns. Cluster 2 has moderate elevation differences, making it relatively well-suited for cycling and active transportation. Additionally, these cities experience a moderate number of days below -15°C, making winter cycling conditions more manageable compared to clusters with harsher climates. The cluster performs strongly in Scenarios A and B, demonstrating the highest number of eligible hexagons, indicating a high potential for cargo bike delivery initiatives. However, fewer eligible polygons in Scenario C suggest that certain urban conditions may limit broader implementation in some areas. From an infrastructure perspective, bike lane diversity is high, reflecting a will to provide citizens with biking infrastructure. However,

the bike lane quality score is lower, indicating that further investment is needed to enhance the safety, connectivity, and overall usability of cycling networks. Given the moderate elevation differences and relatively mild winter conditions, cities in this cluster present a viable opportunity for cargo bike pilot projects, provided that cyclability improvements are prioritized to ensure the efficiency and safety of urban freight deliveries.

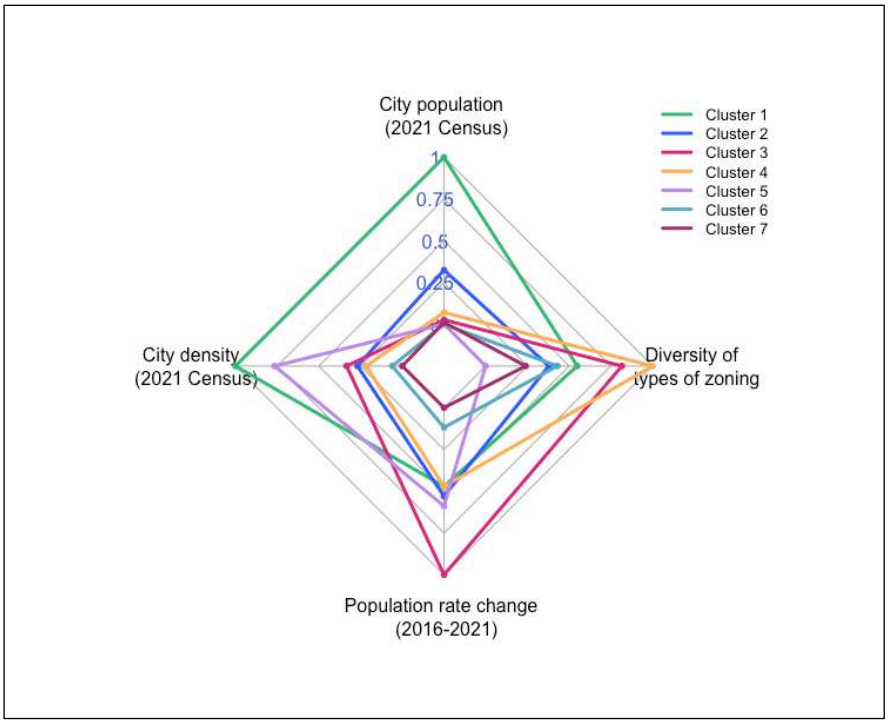


Figure 6.9 Radarchart of all clusters on population indicators

Cluster 3 consists of cities with low overall population levels but a very high diversity of zoning, indicating a mix of land uses that may contribute to a dynamic but spatially fragmented urban structure. These cities exhibit the highest population growth rates, suggesting rapid demographic expansion. Geographically, they are primarily located on the North Shore of Montreal, positioning them within the influence of the metropolitan region while maintaining distinct urban characteristics. From a topographical and climatic perspective, elevation variations are minimal, and winter conditions are relatively mild, making the physical environment conducive to cycling infrastructure. However, despite these favorable natural conditions, cities in this cluster score the lowest in bike lane infrastructure quality, indicating a lack of strategic planning and investment in

cycling mobility. This weakness is further reinforced by the low number of eligible hexagons across all urban scenarios, suggesting that cargo bike delivery initiatives may be difficult to implement. Given these conditions, cities in Cluster 3 are not, for the moment, ideal candidates for immediate cargo bike delivery pilot projects. While the non-controllable environmental factors such as topography and climate are relatively favorable, the lack of developed cycling infrastructure presents a significant barrier. Without targeted investments and policy interventions to improve bike lane quality and connectivity, the feasibility of cargo bike logistics in this cluster remains limited in the short term.

Cluster 4 is characterized by the highest diversity of zoning. However, despite this diversity, the cities in this cluster have relatively low population levels and average-to-low density of population, suggesting that urban development remains somewhat dispersed. The rate of population change is moderate, meaning that while these cities are growing, they are not experiencing the rapid demographic shifts seen in clusters with higher urban expansion.

Geographically, elevation variations are minimal, and climatic conditions are mild, making these cities physically well-suited for cycling infrastructure. Additionally, these cities exhibit low compactness, which can prove a challenge for cargo bike deliveries. Even though Cluster 4 and Cluster 3 share several characteristics, a key distinction between them is the higher number of eligible hexagons across all scenarios (A, B, and C) for Cluster 4. This indicates that, despite some limitations in density and infrastructure, these cities possess a stronger baseline for implementing cargo bike deliveries. With targeted investments in cycling infrastructure and strategic densification efforts, a pilot project for cargo bike logistics could be feasible in this cluster. However, infrastructure upgrades and urban densification efforts would be necessary to maximize the efficiency and viability of such initiatives.

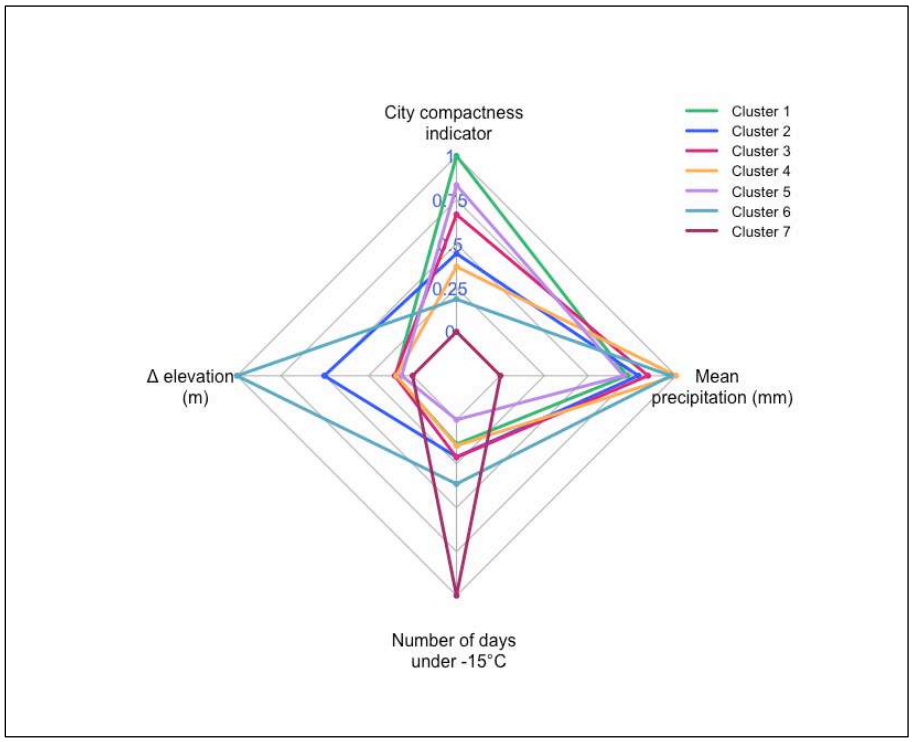


Figure 6.10 Radarchart of all clusters on geographical conditions indicators

Cluster 5 is composed of highly compact and densely populated cities, forming a constellation of satellite cities within the Greater Montreal area. While these cities do not have the largest populations among medium-sized urban centers, they exhibit the second-highest city density, emphasizing their role as well-integrated suburban communities closely linked to the metropolitan core. This strong urban connectivity is further reflected in their high scores for both bikelane quality and diversity, demonstrating a well-developed cycling infrastructure that supports active mobility.

Despite their mild winter conditions, cities in Cluster 5 score very low in all urban scenarios (A, B, and C). This can be primarily attributed to their very low diversity of zoning, as these cities are predominantly residential, with fewer mixed-use developments that could support diverse logistics operations. The lack of commercial and industrial diversity could limit the feasibility of large-scale cargo bike delivery projects under current conditions.

Given their proximity to Montreal and strong cycling infrastructure, cities in this cluster may still benefit from alternative last-mile delivery strategies. Instead of relying on traditional models, the

implementation of micro-hubs strategically positioned near residential areas could optimize cargo bike operations. Additionally, the use of vans as mobile contact points to refill cargo bikes could help overcome the limitations posed by zoning constraints. While direct cargo bike delivery projects may face challenges due to the predominance of residential land use, hybrid models integrating micro-hubs and van-supported replenishment systems could enhance efficiency and feasibility in this cluster.

Cluster 6 consists of low-population, low-density cities characterized by moderate zoning diversity and low population growth rates. These cities experience significant elevation variation, with strong hills shaping the urban landscape. Additionally, moderate to high numbers of very cold days and high levels of precipitation—primarily in the form of snow— create environmental constraints that impact mobility and logistics. In terms of cycling infrastructure, cities in Cluster 6 exhibit average scores for both bikelane diversity and quality, indicating that while some infrastructure exists, it may not be fully optimized for cargo bike logistics. When analyzing urban scenarios, this cluster has moderate to low numbers of eligible hexagons in Scenario A and only minimal improvements in Scenarios B and C, suggesting that under current conditions, large-scale cargo bike delivery operations may face limitations.

Given these challenges, cities in Cluster 6 could consider seasonal pilot projects focused on electric-assisted cargo bikes, which could mitigate the impact of elevation differences and cold weather constraints. Additionally, battery-swapping solutions could enhance operational efficiency, ensuring that cargo bikes can navigate hilly terrain without significant downtime. The strategic placement of micro-hubs would be crucial, with locations carefully selected to account for both topography and accessibility. While year-round implementation may be difficult, a seasonal approach leveraging targeted infrastructure and technology adaptations could provide valuable insights into the feasibility of cargo bike logistics in these cities.

Cluster 7 consists of low-population, low-density cities characterized by low zoning diversity and minimal population change, indicating slow urban growth and a predominantly static land-use structure. The defining characteristic of this cluster is its nordicity, as these cities are located in the northern regions of Quebec, where extreme climatic conditions significantly shape mobility patterns. These cities experience a high number of very cold days, making winter transportation

particularly challenging. However, in contrast to Cluster 6, they are relatively flat, eliminating elevation-related constraints. Despite this, they are also highly non-compact, which increases travel distances and reduces the efficiency of active transportation solutions. In terms of cargo bike potential, Cluster 7 has a moderate number of eligible hexagons in Scenario A but exhibits low

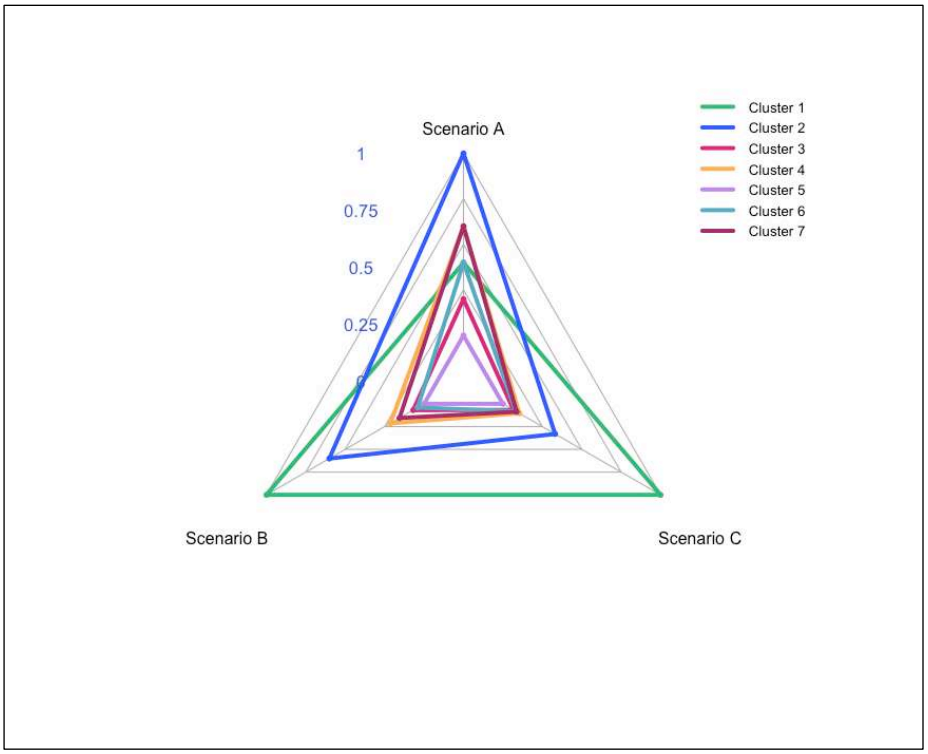


Figure 6.11 Radarchart of all clusters on scenario indicators

growth in Scenarios B and C, suggesting that under current conditions, the feasibility of scaling cargo bike logistics remains limited. A major barrier to implementation is the almost non-existent cycling infrastructure, with very low scores for both bikelane diversity and quality. At present, these cities are not strong candidates for cargo bike implementation, as the lack of infrastructure and long travel distances present significant operational challenges. However, if substantial investments in cycling infrastructure were made, these cities could begin to resemble Cluster 6 in terms of feasibility. In the long term, targeted infrastructure development could make seasonal or small-scale cargo bike projects viable, but such initiatives would require significant policy and financial commitments to enhance the overall cycling environment. Cities in Clusters 6 and 7

experience significant winter challenges, with extended periods of sub-zero temperatures and high snowfall levels. These conditions necessitate specific adaptations for cargo-bike logistics, such as enhanced vehicle design (larger wheels, improved braking systems) and operational modifications (seasonal adjustments, heated rest stations for riders). The results suggest that while medium-sized cities in Quebec hold promise for cargo-bike deployment, their climatic realities must be accounted for in implementation strategies.

Figure 6.12 demonstrates how expert weighting refines the clustering of cities by adjusting their classification based on more realistic logistical and infrastructural constraints.

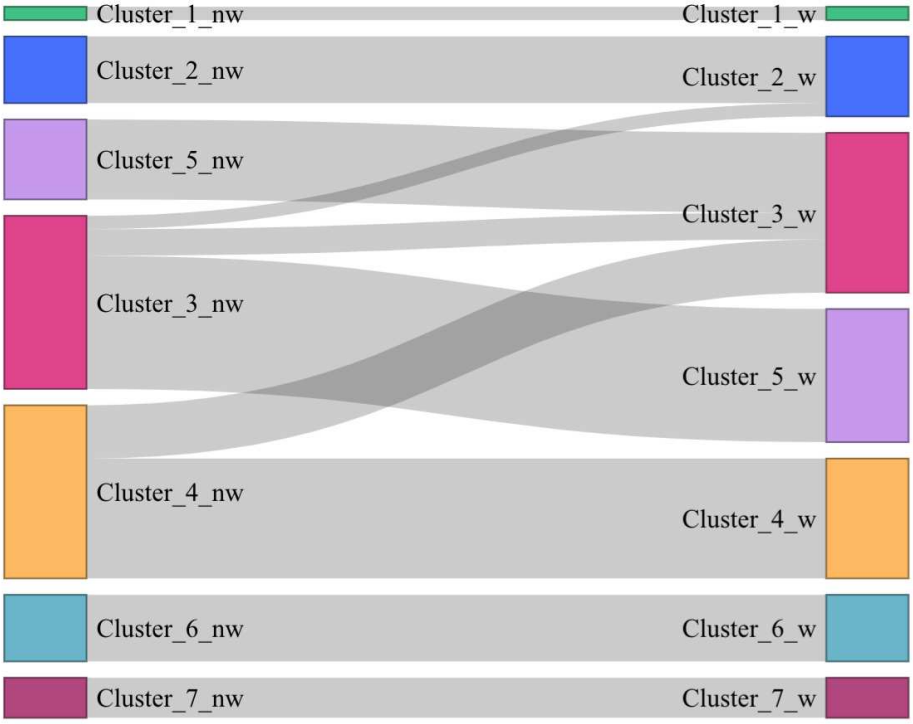


Figure 6.12 Sankey diagram of the changes between non-weighted clusters (left) and weighted clusters (right)

The movement of cities between clusters after applying weighting indicates that some urban and logistical factors are more influential than others in determining cargo bike feasibility. For instance, the fact that certain cities transition from Cluster 3 (moderate feasibility) to Cluster 5 (low zoning diversity, mostly residential areas) suggests that expert judgment has identified zoning constraints as a more critical limitation than originally assessed in the non-weighted analysis. Similarly, if

cities shift towards clusters with better cycling infrastructure (e.g., from Cluster 5 to Cluster 3), it reflects that infrastructure quality has been given more importance in cargo bike feasibility assessments. This reinforces the role of expert-weighted criteria in fine-tuning city classification to align with real-world implementation challenges.

6.5.5 Ranking and clustering cross-analysis for strategic cargo bike deployment

The full table with cities by rank is presented in Table A-2. The comparative analysis of non-weighted and weighted rankings reveals notable shifts in city performance when adjusted for specific weighted criteria. Longueil, Laval, and Saint-Jean-sur-Richelieu maintain their top three positions across both rankings, indicating consistent performance regardless of weighting. However, significant variations in rank are exhibited by some cities. For instance, Chateauguay ascends three places in the weighted ranking, surpassing Terrebonne, Blainville, and Saint-Hyacinthe, suggesting its performance is more favourable under weighted metrics. Similarly,

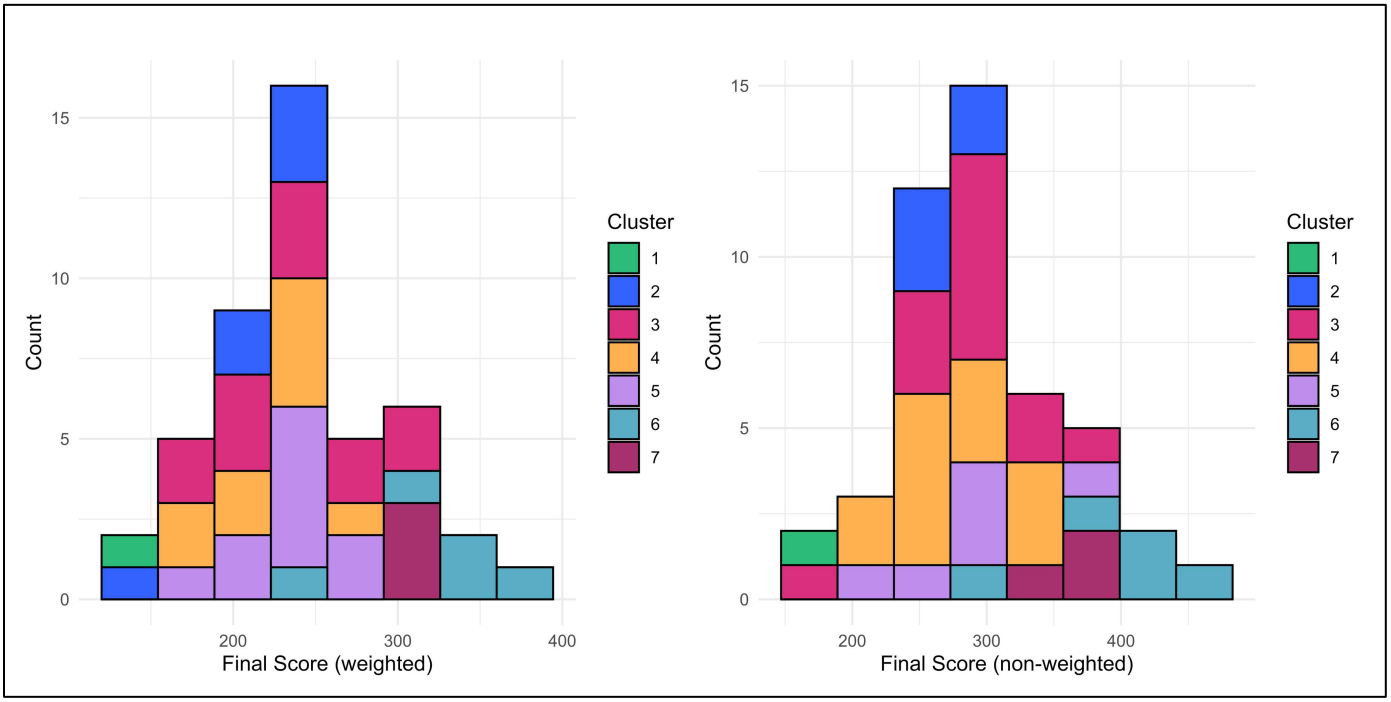


Figure 6.13 Distribution of final scores (i) weighted (left) and (ii) non-weighted (right) by cluster

Brossard descends one rank, while Drummondville exhibits a substantial improvement, rising by seven positions to enter the top 20. The most significant declines are observed in Lévis, which drops seven places, and L'Assomption, which falls eight places, suggesting that their scores are

less robust after the weighting process. Notably, Rimouski ascends six places, and Mascouche advances two, indicating better alignment with weighted criteria. In contrast, cities at the lower end of the ranking, such as Thetford-Mines, Shawinigan, and Sept-Îles, maintain their positions, suggesting that the application of weighting has minimal impact on their comparative standings.

Overall, the weighted criteria appear to moderate extreme values. When linking the clustering and the ranking results, the distribution of the final scores for both the non-weighted and weighted data is similar (Figure 6.13).

The distribution of final scores (Figure 6.13) highlights a clear disparity between clusters in terms of cargo bike delivery feasibility, reinforcing the importance of urban form, infrastructure quality, and climatic conditions in determining potential success. While Clusters 1 and 2 dominate the most favorable ranking range, Clusters 3 and 4 exhibit a more mixed distribution, with some cities ranking moderately well but others scoring higher, indicating greater variability in suitability. This suggests that while some cities in these clusters may support limited cargo bike initiatives, others may require substantial investments in infrastructure and zoning adjustments to become viable candidates. The presence of Cluster 5 cities across a wider score range further confirms that while their strong bikelane networks contribute positively, their predominantly residential zoning may limit broader cargo bike implementation without logistical adaptations such as micro-hubs.

Another key observation from the ranking distribution is the impact of compactness and zoning diversity on feasibility scores. Clusters with low compactness and limited mixed-use zoning, such as Clusters 6 and 7, are underrepresented among the most favorable cities, reflecting their structural limitations in supporting cargo bike logistics. The strong presence of Cluster 3 cities in mid-range scores suggests that while they do not currently exhibit the highest feasibility, their potential for improvement exists—particularly if cities invest in better cycling infrastructure and strategic densification efforts. Additionally, the presence of high-scoring (low-ranking) cities from multiple clusters confirms that local factors such as road network connectivity, specific urban planning policies, and municipal investment in active transportation play an important role, sometimes overriding broader cluster-wide trends.

6.6 Discussion and conclusion

The results of this study highlight the heterogeneity of medium-sized cities in terms of their suitability for cargo bike delivery implementation. Through clustering analysis, cities were grouped

based on key logistical and urban factors such as density, zoning diversity, infrastructure quality, and climatic conditions**.** The findings indicate that high-density, compact cities with well-developed cycling infrastructure (Clusters 1 and 2) are the most suitable for immediate implementation**,** while cities with low zoning diversity and weaker cycling networks (Clusters 5, 6, and 7) require different form of investments, as well as different strategies, to improve feasibility and long-term success**.** Furthermore, the weighted ranking methodology, integrating expert input, refined the feasibility assessment by better capturing the relative importance of infrastructure quality, climate resilience, and urban form**.** However, the disparities between clusters emphasize the need for tailored policies and strategic interventions to support cargo bike adoption in different urban contexts. Our findings underscore the importance of integrating climatic constraints into urban logistics planning, particularly in cities with severe winter conditions.

6.6.1 Policy and strategy insights for cargo bike delivery implementation

The findings from this study provide a framework for the targeted deployment of cargo bike delivery systems based on urban typologies. Rather than applying a uniform approach, strategies must be adapted to the specific constraints and opportunities presented by each cluster. The feasibility of implementation varies significantly across the clusters, with some cities demonstrating immediate readiness for cargo bike logistics, while others require targeted interventions in infrastructure, zoning, and regulatory frameworks. This subsection discusses how policy measures and urban strategies can enhance cargo bike adoption across different urban contexts.

Cities in Clusters 1 and 2 are the most suitable candidates for immediate cargo bike delivery implementation, as they exhibit high compactness, strong cycling infrastructure, and favorable climatic conditions. To fully capitalize on these advantages, municipalities should initiate pilot projects in specific targeted areas**,** allowing for a controlled and measurable assessment of cargo bike logistics. These pilot initiatives can be integrated with the introduction of low-emission zones**,** creating an opportunity to assess the combined impact of cargo bike deliveries and urban sustainability policies. Given the strong enabling factors present in these cities, municipal policies should further prioritize the expansion of cargo-bike-priority zones, particularly in specific contexts such as special events, pedestrian streets etc. The establishment of dedicated loading and unloading zones for cargo bikes and small micro-hubs can further enhance operational efficiency.



Figure 6.14 Examples of transitory micro-hubs in Montreal (left, photo: authors) and Toronto (right, photo : City of Toronto)

In the context of pilot projects, micro-hubs for cargo bikes can adopt a transitory form, such as relocatable shipping containers, which offer a flexible and cost-effective solution for urban logistics. This approach, exemplified by Purolator's initiative in Toronto (Canada) (*Purolator*, 2022), allows for the temporary deployment of micro-hubs in strategic locations, facilitating cargo bike operations while minimizing infrastructure costs for project leaders. The mobility of these modular hubs enables municipalities to test different locations and optimize network efficiency before committing to permanent infrastructure investments (Figure 6.14).

Clusters 3 and 4 exhibit moderate feasibility for cargo bike implementation. However, both clusters must address their infrastructure limitations, as well as their urban sprawl. To improve feasibility, these cities require strategies that focus on infrastructure expansion and urban densification. Investments in high-quality and well-connected cycling infrastructure can significantly enhance cargo bike accessibility and reliability, as well as develop a culture around bikes within the populations. Additionally, incentivizing mixed-use zoning policies can help create denser urban nodes where cargo bike deliveries are more viable by reducing the distance between residential and commercial areas.

Cluster 5, while densely populated, lacks zoning diversity, with most of its urban fabric dominated by residential areas. This presents a logistical challenge, as cargo bike deliveries typically rely on proximity to commercial and industrial zones. To overcome this issue, alternative last-mile logistics strategies should be considered. The development of micro-hubs within residential areas can enable cargo bikes to operate efficiently without requiring direct commercial zoning. Additionally, hybrid delivery models that integrate vans as mobile distribution points can help

bridge gaps in urban freight infrastructure. Local regulatory frameworks should also be adapted to explore the establishment of decentralized urban freight depots, supporting a more efficient integration of cargo bike logistics in suburban environments.

Cluster 6 presents significant challenges due to its strong elevation variations and harsh winter conditions, limiting the feasibility of year-round cargo bike operations. To mitigate these constraints, cities in this cluster should focus on promoting the use of electric-assisted cargo bikes, which can help reduce the impact of elevation differences on delivery efficiency. Additionally, seasonal pilot project of cargo bike deliveries could be one strategy to explore. Cargo bike operations are concentrated in warmer months while complementary modes, such as vans or electric vehicles, support winter deliveries. Further investment in battery-swapping infrastructure can enhance operational viability by allowing cargo bikes to cover longer distances and navigate hilly terrain without extended downtime.

Cluster 7 exhibits the lowest feasibility for cargo bike deployment due to its low density, extreme winter conditions, and lack of cycling infrastructure. In its current state, this cluster is not a suitable candidate for large-scale cargo bike logistics. However, with strong policy interventions, these cities could improve feasibility over time. Long-term investments in cycling infrastructure, particularly in the development of high-quality, all-season bike lanes, are necessary to build a foundation for active transportation. Encouraging densification strategies that create more compact urban nodes can also enhance the viability of last-mile logistics.

This study provides a novel methodology for assessing the feasibility of cargo-bike delivery initiatives in medium-sized cities, utilizing open data and a mixed-methods approach. By integrating spatial analysis, land use classification, and a Delphi survey with industry experts, the research establishes a framework for identifying cities best suited for cargo-bike logistics. The study also introduces a scalable clustering method that categorizes cities based on urban form, climate, infrastructure, and logistics potential, offering policymakers and urban planners a data-driven tool to support sustainable freight solutions. Moreover, the ranking method, incorporating expert-weighted criteria, refines the prioritization of cities for pilot projects and long-term implementations. Ultimately, this work highlights the untapped potential of medium-sized cities for cargo-bike logistics, bridging a critical gap in urban transportation research and advancing sustainable last-mile delivery strategies.

6.6.2 Limitations and future studies

Despite its innovative approach, this study presents several limitations. The reliance on open data, while ensuring transparency and reproducibility, also introduces constraints due to the lack of standardized and up-to-date datasets across municipalities, particularly regarding freight flows and future cycling infrastructure expansions. Additionally, the methodology assumes that residential zones primarily act as freight-receiving areas, which may oversimplify the dynamics of urban logistics. The study also faces limitations in its ranking approach, as the applied method, though straightforward and interpretable, does not allow for fine-tuned weighting adjustments or sensitivity analyses that could refine city classifications. Moreover, climatic conditions and topographical challenges are considered at a macro scale, which may not fully capture localized barriers to cargo-bike implementation. Finally, the absence of real-world pilot testing means that the findings, while robust in their theoretical framework, require empirical validation through practical deployment in medium-sized cities. Future research should prioritize real-world implementation by conducting pilot projects in selected urban areas, allowing for the assessment of operational performance, economic feasibility, and user acceptance. Another methodological limitation concerns the use of Shannon's entropy as a proxy for land use diversity within urban hexagons. While this measure captures the heterogeneity of land uses in a given area, it does not account for the spatial arrangement or proximity between different functions, which may significantly affect delivery feasibility and infrastructure design. For instance, a hexagon with evenly distributed but spatially segregated land uses might exhibit a high entropy score, yet offer little practical integration for cargo-bike operations. Furthermore, entropy does not reflect temporal dynamics, such as fluctuating demand across time periods or days of the week, which are crucial in logistics planning. As such, while entropy offers valuable insight into land use complexity, it should be complemented in future studies by spatial metrics (e.g., land use adjacency or connectivity) and temporal activity data to provide a more nuanced understanding of delivery potential. To enhance the effectiveness of these initiatives, a refined method for ranking cities based on their suitability for cargo-bike logistics is essential. The current ranking approach provides a structured comparison using multiple criteria; however, a more sophisticated model could significantly improve decision-making accuracy. In particular, integrating multi-criteria decision analysis (MCDA) techniques, such as the Analytic Hierarchy Process (AHP) or PROMETHEE, would enable dynamic weighting of factors, ensuring a more precise evaluation of urban contexts.

While this study focuses on medium-sized cities in Quebec, its methodology can be adapted to other regions with varying urban forms. Expanding the framework to different geographical contexts would provide valuable insights into how local conditions influence cargo-bike adoption. However, successful implementation depends not only on city characteristics but also on supportive urban policies and infrastructure. Elements such as micro-consolidation hubs, designated cargo-bike lanes, and financial incentives play a crucial role in integrating cargo bikes into existing freight systems. Therefore, future research should evaluate the effectiveness of these policy measures, assessing the impact of subsidies, tax incentives, and regulatory adaptations, including low-emission zones (LEZs) and dedicated loading areas for cargo bikes. Finally, technological advancements continue to shape the feasibility of cargo-bike logistics. Innovations such as extended battery life, increased load capacity, and improved weather resilience could significantly enhance the operational efficiency of cargo-bike fleets. Given the diverse climatic and infrastructural conditions of medium-sized cities, future studies should analyze the real-world impact of these advancements, ensuring that emerging technologies align with the practical needs of urban freight logistics. Future research should further explore technological and infrastructural adaptations that can enhance the viability of cargo bikes in difficult environments (extreme heat or extreme cold, for example). By linking pilot studies, refined ranking methodologies, policy evaluations, and technological innovations, future research can create a comprehensive roadmap for scaling up sustainable cargo-bike delivery solutions.

CHAPITRE 7 ARTICLE 4 : « A MICROMOBILITY SOLUTION FOR HOUSEHOLD LOGISTICS? DETERMINANTS OF SHARED BICYCLE TRAILERS USAGE »

Cet article est le fruit d'une collaboration avec Joséphine Mariquivoi, doctorante à la « Vrije Universiteit Brussel » (VUB) au sein de l'équipe de recherche *Mobilise*. Montréal et Bruxelles ayant des initiatives de remorques à vélo similaires, cette collaboration a été l'occasion de déterminer et comparer les déterminants des emprunts de ces remorques à vélo. Cette collaboration a permis la rédaction de l'article intitulé « A micromobility solution for household logistics? Determinants of shared bicycle trailers usage » qui est en cours de révision dans le journal « *Research in Transportation Economics* », au sein d'un numéro spécial sur « *Balancing emerging logistics services in a sustainable urban freight environment* ». L'article a été soumis le 6 novembre 2024. La contribution de Capucine Paque lors de l'été 2024 a permis d'accélérer la récolte de données sur le terrain.

A MICROMOBILITY SOLUTION FOR HOUSEHOLD LOGISTICS? DETERMINANTS OF SHARED BICYCLE TRAILERS USAGE

Joséphine Mariquivoi, Suzanne Pirie, Philippe Lebeau, Koen Mommens, Martin Trépanier et Walter Rei

7.1 Abstract

Cycling is a solution to decarbonize urban transport of people and goods. Shared solutions, such as shared bike trailers, facilitate the expansion of micromobility offerings within urban areas. However, such solutions are currently understudied, hence underestimated for freight transport in cities. Based on operational data of two shared bike trailer services, we have developed a model based on a Quasi-Poisson model and a clustering method with socio-demographic and geographic data that explains the use of these services. This paper explains how shared bike trailer networks can have success in different urban environments and analyses how this type of shared micromobility vehicles can be a cycle logistics solution applied to consumer logistics. The results show success and failures factors of trailers in two different cities on different continents. Socioeconomic factors and zoning characteristics, and accessibility to transport options play significant roles in determining the success of bike trailer loans, with residential and commercial

zoning being particularly influential in Montreal, while service zoning negatively affects trailer use in Brussels. Successful trailers are mainly located in residential and mixed-use areas. Trailers are used for different purpose, such as house moving, grocery shopping and leisure activities involving freight transportation. This mean a possibility for bike trailer to be one solution in the choices of alternative mobility to avoid vans or cars.

Keywords: cycle logistics; micromobility; shared mobility; emerging logistics; household logistics

7.2 Introduction

Cycling mobility has gained major attention from researchers as well as interest for local and national authorities. Since the 2000s, the resurgence in cycling has now reached major European cities (Héran, 2015). In Brussels, the number of cyclists recorded during the morning peak hour in 2022 showed an increase of 43.7% compared to 2021. On the other side of the Atlantic, Statistics Canada reports that 1 in 5 Canadians (20.4%) who cycled to work lived in the Montreal area (Government of Canada, 2024). In Montreal, across the 33 automatic data counters for cyclist, there is a steady increase in the number of cyclists of 6.13% (Pronovost, 2023). Some cities, such as Paris, have even seen bikes exceed cars during peak times (Breteau, 2023). Moreover, bike sharing is described as the 21st century's universal solution for making urban transport more efficient and sustainable (DeMaio, 2009). This shift towards biking can be explained by the development of proper biking infrastructures to ensure the security of cyclists and the reduced access to certain parts of the cities thanks to low emissions zones and pedestrian zones.

A conventional bike can carry a limited number of everyday objects, such as parcel pick-ups or groceries. This is why the increase of cycling in urban areas is coupled with the development of different types of bikes and trailers that can carry loads or several people (mostly children) at a time. We observe that 41% of bikes transporting children in Brussels are cargo bikes and cargo bikes are 8% of bikes counted in 2022 (Lahon & De Mey, 2022). Indeed, the development of cargo bikes has been identified as a solution for more active mobility in Europe (Riggs, 2016). When it comes to cargo bikes for commercial freight transportation, Peppel et al. (2022) estimate that it will become one of the preferred mode of transportation in 2040 if enough infrastructures (specific parking space, wide enough bike lanes etc.) are developed. However, cargo bikes for private transport remain expensive (A. Thomas, 2022) and in that regard, bike trailers when available

represent an alternative to the possession of a cargo bike. Bike trailers allow the use of normal bikes with an added capacity up to 100 kg, depending on the build and size of the trailer.

For both Brussels and Montreal, trailer initiatives stem from citizen movements to provide local populations with shared bike trailers aimed to transport goods. The initiative in Montreal, named *LocoMotion*, started in 2018. *Remorquable*, the Brussels initiative, started in 2019. In Montreal, citizens can register for free to rent different types of vehicles, such as bikes and cargo bikes, bike trailers and cars. The bikes, cargo bikes and cars belong to private individuals who choose to rent their vehicles, while the bike trailers belong to *LocoMotion*. The bikes, cargo bikes and trailers are free to rent, and the cars can be rented for a small fee that mainly covers the price of fuel and insurance. Currently, in Montreal, 80 trailers are available to rent. *Remorquable* is a non-commercial organization registered in Belgium. In Brussels, members can choose between different levels of membership, according to their needs or their financial situation. There are 27 bike trailer depots, called *"Remorquothèque"* (trailer library) with a total of 32 trailers. In both initiatives, members can book their trailers via a mobile application. Members are responsible to put back the trailers and ensure that they are properly locked and ready for the next user. In Brussels, trailers are mostly located near social, cultural and militant centers, whereas in Montreal, trailers are mostly located near commercial streets, on the sidewalk and in back alleys.

While the cargo bike market the logistics industry is rapidly growing and is both visible and encouraged, less is known about its use for private individuals. To the best of our knowledge, there exists very little scientific literature about freight mobility tailored to sporadic use for citizens within urban contexts. Bike trailers fit within the scope of micromobility but have yet to be studied thoroughly as they represent emerging logistics initiatives for freight transportation. Moreover, the use of bike trailers within Montreal and Brussels can be perceived as the continuity of potential modal shift from cars within the specific scenario of household logistics. To the best of our knowledge, this has not yet been studied within the context of the last-mile problem and household logistics.

While the initiatives are very similar on paper, the geographical, socio-economic and cultural contexts make them unique. However, both initiatives represent a niche service of micro-mobility organisation and original case studies. The challenge for emerging freight transport solutions is to find their place in cities to ensure that they are used and adapted within their specific context.

Studying these shared trailers initiatives focused on the transport of goods allows us to develop a method to address the lack of knowledge about these potential uses, even though the geographic contexts are different. The two main research questions of this research are:

- What are the success or failure factors of shared bike trailer services?
- How can we compare different uses of bike trailers between two cities with different geographical contexts?

Both research questions are answered using datasets from the bike trailer initiative from Montreal and Brussels. The next part of the article is a literature review on consumer logistics, cycle logistics as well as micromobility research. The third section covers the materials and methods used to answer the research questions, including model presentation and assumptions. The fourth section presents the results for the generalised models as well as the clusters. Finally, the last section presents the conclusion, discussion and limitations of the article.

7.3 Literature review

This study on shared bike trailers stands at the intersection of consumer logistics, cycle logistics and shared micro-mobility services, which are reported in this review.

7.3.1 Shared – micromobility

Micromobility is a relatively new field of research and regroups the use of micro-vehicles for transportation (Oeschger et al., 2023). As highlighted in Behrendt et al. (2023), several definitions exist for micromobility. However, definitions tend to converge towards the concept of vehicles with low mass (max. 350 kg), low speed (below 45 km/h) and which travel over short distances (International Transport Forum, 2020). Typically, these types of micro-vehicles include (e-) scooters, (e-) bikes, (e-) cargo bikes, shared (e-) bikes systems etc. The International Transport Forum (IFT) specifies four classes of vehicles that cover the range of micromobility, summarized in Table 7.1.

Table 7.1 Description of micro-vehicles classes (IFT)

Class	Maximum speed (km/h)	Maximum weight (kg)	Example(s)
A	25	35	Regular bike and e-bike
B	25	35-350	Cargo bikes and e-cargo bikes, cargo trikes, bike with trailer
C	25-45	35	e-bike, e-scooter
D	25-45	35-350	e-scooter, scooter

Micromobility services are an effective tool as an alternative to the use of private cars. In their study on modal substitution with shared micromobility services, Bösehans et al. (2024) highlight that private cars are mostly substituted by shared cars or e-cars (36 % and 18 % respectively), shared e-cargo bike (16%) and shared bike (9%). Micromobility services can also improve connectivity with existing networks (Oeschger et al., 2020) and even to substitute public transport trips (Campbell et al., 2016). Current studies on shared - micromobility strongly focus on (e-) scooters and bike sharing systems. Studies also include examples (e-) cargo bike sharing. Table 7.2 summarises the results by shared-micromobility mode. Driving encompasses private cars, shared cars, using a taxi or on demand services such as *Uber* or *Lyft*. Public transport includes the use of subway, bus, tram or train.

Table 7.2 Mode substitution in studies on shared micro-mobility

Mode	Authors, date	City, country	Substitutes …			
			Walking	Driving	Public transport	Biking
E-scooter and scooters	Reck et al. (2022)	Zurich, Switzerland	X	X	X	X
	Christoforou et al. (2021)	Paris, France	X		X	
	James et al. (2019)	United-States	X	X (private cars and taxis)	X	X
Bike sharing et e-bike sharing	Ma et al. (2020)	Delft, the Netherlands	X	X (private car)	X	X (private bike)
	Teixeira & Lopes (2020)	New-York, USA			X (subway)	
Cargo bike and e-cargo bike sharing	Becker & Rudolf (2018)	Germany and Austria		X (private car)		
	Bissel & Becker (2024)	Germany		X (private cars)		

In their new definition of micromobility, Behrendt et al. (2023) adds the notion of freight transportation, especially thanks to cargo bikes as a mode of transport. Cargo bikes which refer to "a wide variety of adapted cycles, designated to carry heavy and bulky loads or passengers" (Narayanan & Antoniou, 2022b). The use of cargo bikes in the context of personal mobility is being more and more researched. Several studies focus on the modal shift (effective or potential) that this type of vehicle has induced, linked with the idea of "demotorization" (Marincek et al., 2023). This modal shift to cargo bikes can even support the reduction of trips done with private cars. In their study at a national level in Germany, Bissel & Becker (2024) identify a potential for car ownership reduction ranging from 7.4 % to 8.1 %. The use of cargo bikes can also be linked to a decrease in externalities, either by substituting private cars (in the context of private transport) (Becker & Rudolf, 2018) or trucks and vans (in the context of urban freight transport) (Koning & Conway, 2016). In their literature review, Vasiutina et al. (2021) cover the different methodologies used to calculate emission reductions. However, cargo bikes, whether for personal transport or freight transport, can be remain expensive and price can become a barrier to their adoption (Bourne et al., 2020; A. Thomas, 2022). This is why shared initiatives, such as studied in Hess & Schubert (2019) represent an interesting alternative to owning a private cargo-bike, as the respondents of their survey mention the need for this service on an irregular basis. Other barriers to the adoption

of cargo bikes for private use include fear of theft (Bourne et al., 2020), lack of adapted parking space (Riggs, 2016), lack of infrastructure, weather dependence (Bissel & Becker, 2024; Malik et al., 2023) and safety concerns (Bissel & Becker, 2024; Hess & Schubert, 2019b).

Shared biked trailers systems are defined as a micromobility system from cargo bikes modes. First, "conventional bike with a trailer" is a common category within cargo cycles's typology (Narayanan & Antoniou, 2022b). Secondly, to a certain extent, it is possible to argue that shared bike trailers could be included within the class A of micromobility, as shared bike trailers allow consumers to keep the flexibility of their regular bikes and use the trailers when needed. Furthermore, most published articles about shared-micromobility services focus on the transportation of people, highlighting the need for more research tailored for urban logistics.

7.3.2 Cycle logistics

Micromobility concepts can also be used in logistics context. Particularly, cycle logistics have been developed as a sustainable solution for the last mile in urban areas. Cycle logistics can be broadly defined as the commercial activity of transporting goods using bikes, and especially cargo bikes. Cargo bikes are an intermediate vehicle defined within the category of with electric pedal assistance limited to 1 kW (Héran et al., 2022). In the context of this study, bike trailers can be considered as a subcategory of the larger family of cargo bikes. The use of cargo bikes for urban freight transport is relevant in cities with high population density (Choubassi et al., 2016) and therefore demand density (Llorca & Moeckel, 2020) and proper cycling infrastructure (Gonzalez-Calderon et al., 2022). To ensure the success of deliveries with cargo bikes, the characteristics of delivery routes must be taken into account (M. Sheth et al., 2019). The presence of urban consolidation centers helps to mitigate the effects of battery range and smaller capacity of cargo bikes and to improve efficiency (Fikar et al., 2018b). However, several variables can also become a barrier to the adoption of cargo bikes for freight urban deliveries, such as weather (Giordano et al., 2022; Malik et al., 2023), topography (Giordano et al., 2022) and trip length (Malik et al., 2023). While the literature on the use of cargo bikes for freight transport in professional contexts is rapidly evolving, as is the research on their use for transporting people (such as children or older adults), there remains a paucity of studies specifically addressing the transport of freight within households using cargo bikes.

7.3.3 Household logistics

Recent studies tend to consider consumer or their household as an element of the urban freight transport chain among studies on alternatives for the last-mile delivery sector (Beckers & Cant, 2023; Cebeci et al., 2023). Up to now previous studies have analysed how consumer shifts from passive towards deliveries to an active role (Monnot et al., 2023), such as highlighted in the feasibility study of using drop-off boxes and thus, co-creating an alternative within the supply chain (Risher et al., 2020). These studies encompass the role of the consumer or household in transporting purchased goods, defined as consumer logistics. This concept is a broad term defined by Granzin & Bahn (1989) as the "consumers' participation in the movement and handling of goods from the point of acquisition to the point of consumption or final disposal".

The previous definition of consumer logistics by Granzin & Bahn (1989) only covers a mercantile point of view, whereas goods can also be transported within non-merchandised activities. Therefore, for the present study, the definition adopted is closer to household logistics, to encompass all activities generating freight transportation. There is little published research on the alternative mobility choices for goods transport by consumers. Furthermore, there is a lack of studies about households transporting goods with cargo bikes. This is why this study on bike trailers aims at providing insights on how households who choose to use bike trailers use them and on what influences this type of initiatives to perform.

7.4 Materials and methods

In this section, we introduce the various datasets used in our analyses and outline the models applied to perform the numerical evaluations aimed at answering the research questions. Additionally, we review the underlying assumptions of these models to ensure their statistical validity.

7.4.1 Data

The data primarily comes from *LocoMotion* and *Remorquable* and is enriched by census data and different sources of open data available from the cities of Montreal and Brussels.

7.4.1.1 Operational dataset

The data is provided by *LocoMotion* (Montreal) and *Remorquable* (Brussels). Table 7.3 provides the description of each variable and its availability for each city. Variables followed by "*" are based on declarations provided by the users when they end their trip with the trailers. The dataset for Montreal spans from May 2020 to April 2024, with a total of 5,973 loans. For Brussels, the data was obtained from a self-administered survey and data from operators from February 2021 and August 2024 with a total of 1,687 loans. Each trailer's loan creates a data line with this following information.

Table 7.3 Description of available information for the two initiatives

Variable	Montreal	Brussels
Trip information		
Date of trip	X	X
Trip length	X	X
Distances*	X	X
Trip purpose*	X	X
Load weight*		X
Trailer location	X	X
Trailer information		
Trailer ID/number	X	X
Date of commissioning	X	
Depot place	X	X
Maximum capacity (kg)	X	
Type of trailer	X	
Replaced vehicle		
Type of vehicle (survey)		X
Euro norm (survey)		X

The nature of the load was determined during a survey carried out at the moment of booking on the *Remorquable*'s website, whereby the user was invited to select an activity from 5 categories: house moving, food, tools, construction and other. The *LocoMotion* dataset includes an open-ended text box for users to describe why they needed to borrow the trailer after completing a journey. To analyse the results, all responses were categorised using Python and natural language processing

packages, such as *nltk* (Bird et al., 2009). In the dataset 5,614 lines contain information entered by users at the end of their trip. Using a word frequency algorithm provided with the *nltk* package, only the main reasons are considered. For Montreal, the text analysis yields six main categories: groceries, services, transport of small goods, moving and manual labour.

7.4.1.2 Land use and census data

The initial phase of the analysis involves geographically characterizing the local environment surrounding each trailer depot within an 800-meter buffer zone. This choice of buffer is derived from the car-sharing literature as an acceptable walking distance to reach a vehicle (Celsor & Millard-Ball, 2007; Grasset, 2009) and corresponds to approximatively a ten-minute walk for an adult individual with no disabilities. First, around each trailer location, the zoning mix is calculated within an 800 m buffer, this data are precise and available to characterize built environment and land use – a possible factor to explain travel behavior (De Vos, 2015; Y. Zhang et al., 2023). The zoning mix is divided into nine categories (1) residential, (2-3) manufacturing industries, (4) transport, communications and public services, (5) commercial activities, (6) services, (7) cultural and leisure activities, (8) production and extraction of natural resources, (9) non-operated buildings and bodies of water. These nine categories are based on the classification of land-use by the Quebec government (MEFQ, 2024) To perform this zoning analysis, two datasets are used, one for each city. In Brussels, the cadastral categorization is used, at the statistical unit level (Statbel, 2023). In Montreal, the land use evaluation is used, which details the primary use of each building at the provincial level of Quebec (Données Québec, 2023). More information about the geographical matching between the two countries is presented in Table B-1. Based on this zoning analysis, an average profile environment for both cities is determined. While residential land use is predominant in both cities, with 94.30% for Montreal and 92.43% for Brussels, respectively. We observe that Brussels has more mixed uses with 5.94% of commercial zoning. Detailed results about the zoning mix for each city can be found in Table B-2. Then, from the location of the trailer, the following socio-demographic data has been extrapolated from the statistical sector or census data for each city: median taxable income, average age, household motorisation rate, unemployment rate and population density. Sources for each variable added can be found in Table B-5. To compare the two median taxable incomes, the variable for the city of Brussels is converted to Canadian dollars (by applying the following approximate conversion rate: 1E = 1.5 $CAD). Finally, another set of variables contains the distances to geographical points that reflect the accessibility of the location,

such as public transport stops (train, metro, tram), bicycling infrastructure, and other sharing networks (bikes, cars, bike's trailers themselves). More information about the specific contexts of Montreal and Brussels will be detailed in the results section of this paper.

7.4.2 Rationale behind model choice

This Section aims to present the different steps that guided the model choice to answer the first research question, which seeks to find the success and failure factors of bike trailer sharing services.

7.4.2.1 Model estimation: generalized model with Quasi-Poisson distribution

The data at hand is count data and our dependent variable is the number of times a bike trailer is loaned. The data follows a Quasi-Poisson distribution Figure 7.1, characterized by a mean of 2.02 and a variance of 4.11, indicating overdispersion relative to the Poisson model. To address our first research question, which aims to explain the factors behind the success of trailer locations based on their utilization rate, we chose a generalized model with a Quasi-Poisson distribution to account for overdispersion while modeling the factors affecting bike trailer usage.

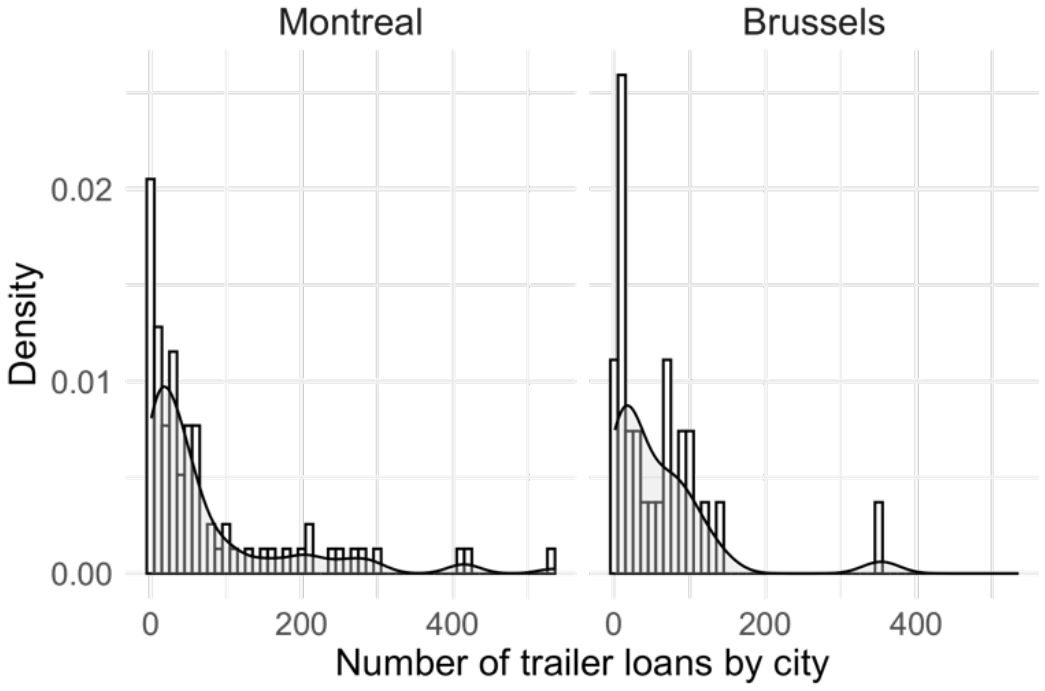


Figure 7.1 Data distribution for Montreal and Brussels

7.4.3 Correlations between variables

Several of the variables included in the models are found to exhibit a degree of correlation. From the correlation table (Table B-3), it can be observed that there is a strong negative correlation between the proportion of commercial zoning (CUBF_5) and the unemployment rate (unemployed_rate) (-0.76). Similarly, the proportion of residential zoning (CUBF_1) exhibits a negative correlation with the proportion of transportation zoning (CUBF_4) and the proportion of commercial zoning (CUBF_5), with respective correlation coefficients of -0.53 and -0.65. As might be expected, there is a strong positive correlation between the proportion of manufacturing zoning (CUBF_3) and the proportion of transportation zoning (CUBF_4), with a value of 0.8. This is because industrial zones are always characterized by these two types of zoning. Additionally, the negative correlation between median taxable income and the unemployment rate (-0.79) is an unsurprising outcome. Of note is the moderate positive correlation between the number of trailers within 1 km and trailer loans history (0.31), indicating a potential relationship between the proximity of trailers and loans.

7.4.4 Factor analysis and communalities

To reduce the number of variables and to avoid using strongly correlated variables for the different models (see Table B-3), a factor analysis is performed on the normalized variables. The factor analysis is performed on R with the library *Psych* (Revelle, 2024). Factor analysis is a common method, used in social and human sciences, to explain covariance of observed data and may help to determine factor numbers (Hoyle & Jamieson L., 2004). To perform the appropriate factor analysis for this study, the parameters used are the *Equamax*, which is used to balance the variance of the squared loadings across both factors and variables. This allows the factor loadings to be more easily interpretable. This provides us with three main factors (MR1, MR2 and MR3). The three factor loadings correspond to the correlations between the factors and the variables (Table 7.4).

Table 7.4 Factor loadings and communalities

	MR1	MR2	MR3	Communality
Proportion of the variance explained	23 %	13 %	11 %	-
Population density	0.82	-0.07	0.10	0.69
Unemployment rate	-0.77	0.14	-0.49	0.85
Proportion of zoning for services (CUBF_6)	0.70	0.51	0.14	0.78
Distance to the nearest bus station	-0.65	-0.10	-0.23	0.49
Median taxable income	0.63	-0.10	0.38	0.56
Distance to the nearest train station	0.52	-0.34	0.10	0.41
Number of trailers within a 1 km radius	0.50	-0.06	-0.19	0.29
Proportion of zoning for cultural activities (CUBF_7)	0.48	0.04	-0.09	0.24
Distance to the nearest bike sharing station	-0.42	-0.13	0.29	0.28
Mean of household size	-0.42	0.21	0.19	0.26
Distance to nearest subway or tram stop	0.39	0.07	0.31	0.26
Distance to nearest car sharing station	-0.24	-0.03	0.05	0.06
Household car possession	0.03	0.20	0.92	0.89
Proportion of commercial zoning (CUBF_5)	-0.51	0.27	-0.70	0.83
Mean household age	0.20	-0.10	0.43	0.24
Proportion of manufacturing zoning (CUBF_3)	0.10	0.82	0.26	0.74
Proportion of residential zoning (CUBF_1)	0.20	0.42	-0.72	0.74
Distance to the cycling network	-0.09	0.53	0.07	0.29
Type of street in which the trailer is parked	-0.08	-0.14	0.06	0.03

The initial factor, designated MR1, appears to encapsulate the interconnection between urban infrastructure and socioeconomic variables, including population density (0.82), median taxable income (0.63) and zoning for services (0.70). Given the negative correlation coefficient of -0.77, it can be inferred that MR1 represents high-income and densely populated areas. The second factor, designated MR2, appears to represent a factor linked with a higher proportion of non-residential zoning and network characteristics. The correlations are positive and high for the proportion of manufacturing zoning (0.82) and distance to the cycling network (0.53). Additionally, the positive correlation with the proportion of zoning for services (0.51) and residential zoning (0.42) indicates

a combination of land uses, potentially representing areas with more diverse urban planning characteristics. The third factor, MR3, appears to reflect aspects of car dependence and commercial zoning. The very high loading on household car possession (0.92) and negative loading on proportion of commercial zoning (-0.70) indicate that MR3 may represent areas that are more car-dependent, with lower commercial activity and a heavier reliance on personal vehicles for transportation. Based on the factor loadings, it is possible to compute the communalities. The communality for a variable is defined as the proportion of the variation in the variable that is explained by all the factors (in this case, three factors). The communalities for each variable are presented in Table 7.4.Subsequently, a cut-off value for the communalities is selected in order to identify the relevant variables. The cut-off value chosen here is 0.55, based on the median of all variables. The eight selected variables are presented in bold in Table 7.4.

7.4.5 Clustering method

The following section aims at presenting the clustering method used and the number of clusters chosen, as well as the clustering variables and indicators developed to analyse the results. The clustering method presented answers the question how to compare the loaning behaviours between the two cities. Through the clustering method we aim to show variations of explanatory factors according to different type of trailer loans. These results will help to identify and describe different profiles of trailer use and their characteristics between the two cities.

7.4.5.1 Clustering variables and correlations

The clustering variables are chosen in order to highlight similarities and differences between trailer use for both shared bike services based on the trailer's data. The four selected clustering variables are (i) the trailer utilisation rate divided by the number of months since the trailer was brought into service (trailer_loans_histo), (ii) the mean loan time for each trailer (mean_time), (iii) the mean distance traveled by the trailer (mean_dist) and (iv) the proportion of commercial zoning within 800 meters of the trailer (CUBF_5). The trailer utilisation rate corresponds to the frequency of use of the trailer, the mean time and mean distance are operational values which characterize the use of trailers and finally, the proportion of commercial zoning helps to characterize the direct environment in which the trailer evolves. The highest correlation amongst the variables is 0.31 (Table B-3), with the majority of correlations oscillating between -0.1 and 0.2. This indicates that

the selected variables are not excessively correlated, thereby ensuring their suitability for the clustering method.

7.4.5.2 Clustering method choice and number of clusters

The clustering method chosen for this study is a k-medoid method, also known as Partition Around Medoids (PAM). The K-medoid clustering method groups data points into clusters by selecting actual data points (medoids) as the cluster centres. The medoid is the data point within each cluster that minimizes the sum of dissimilarities to all other points in the same cluster, making it a more representative and robust center compared to the centroid used in k-means clustering. This approach minimises the sum of dissimilarities between each point and its nearest medoid, making it more robust to noise and outliers than the k-means method. Moreover, the k-medoid method is well-suited for smaller datasets with mixed types such as the one used in this study. The number of clusters is determined using the silhouette method (Figure 7.2).

In this analysis, the dissimilarity measure is the Euclidean distance. Euclidean distance is chosen to handle effectively continuous and scaled variables. The results from the silhouette method indicate that 5 clusters would be optimal. However, after trial and error, four clusters provided more interpretable results. Therefore, only four clusters were used to perform the clustering. Before performing the clustering, all variables are scaled. All computations are done using R and the library Cluster (Maechler et al., 2023).

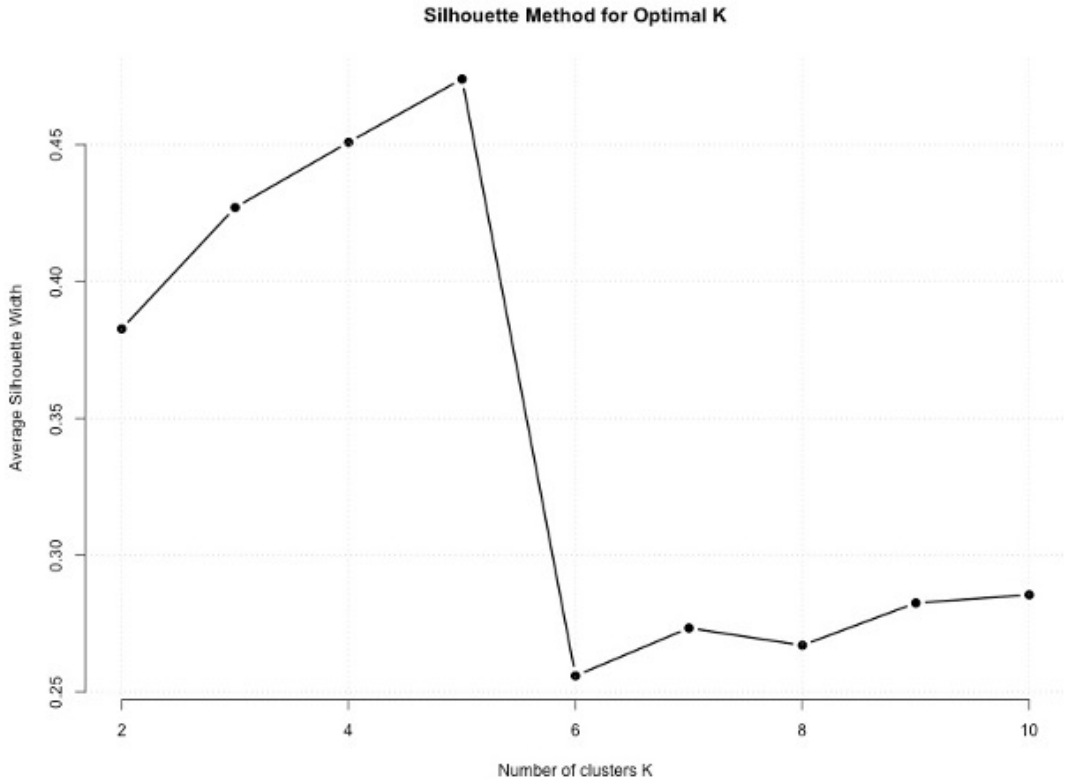


Figure 7.2 Results of the silhouette method

7.4.5.3 Clustering indicators

To analyse the results, indicators are created based on all the collected variables previously presented. The indicators can be grouped into 4 categories: accessibility, operational, network and socio-demographics (Table 7.5).

Table 7.5 Clustering indicators by category

Category	Indicator(s)
Accessibility	Mean distance to cycling network (in meters)
	Mean distance to nearest bike sharing station (in meters)
	Mean distance to nearest tram or subway station (in meters)
	Mean distance to nearest train station (in meters)
	Mean distance to nearest bus stop (in meters)
	Mean distance to nearest car sharing station (in meters)
Operational	Mean amount of time the trailer is loaned (in minutes)
	Mean distance traveled by the trailer (in km)
Network	Mean number of trailers within a 1 km buffer around the trailer
Socio-demographics	Mean taxable median income (in $CAD)
	Mean of population density
	Mean of household age (in years)
	Mean of household size
	Mean of household car possession (number of cars per household)
	Unemployment rate

7.5 Results

The results sections are divided between the descriptive results from the bike trailer loan initiatives themselves (7.5.1), the results from the generalised model (7.5.2) and finally the results of the clustering process (7.4.5).

7.5.1 Descriptive statistics

In Montreal, the trailers are mostly used during the weekends, with a total of over 40 % of the observations. During the week, Tuesdays and Fridays represent a little over 25 % of the reservations. In Brussels, trailers are used the most during the week, especially on Mondays and Fridays, which represent 41 % of the reservations. Weekends only represent 15% of the reservations. This can be explained by the fact that the users in Montreal are mostly individuals using the bike trailers for their personal needs, whereas the users in Brussels tend to work more in associations and use the bike trailers on a semi-professional basis. Indeed, there are two types of subscription, allowing us to identify the nature of the load: 86% of subscribers are private individuals and 14% are professional organizations in Brussels. Moreover, the Belgian trailers

seem to replace trips with motorized transports, while 65% of loans are replacing cars and 14% are replacing vans. This information is not available for Montreal. In Montreal, bike trailers are rented on average 397 minutes by loan (~ 6.5 hours), with a median of 150 minutes (~2.5 hours). The distances are estimated by the users at the end of their trip, which may be cause for some inaccuracies. Bike trailers travel an average of 16 km for Montreal per loan with a median of 20 km, and respectively 11km and 15km in Brussels. Information on types of loading are also indicating a semi-professional use.

The number of members in Brussels increases from year to year, from 40 in 2021 to 96 in 2023. In Montreal, around 2,000 citizens join each year, but only around 15 % are active members. Indeed, in Brussels the most frequent type of loading was for moving, followed by groceries then other, and finally tools (n=86) and construction (n=102), with less than 10% in each category (Table B-4). For Montreal, the results of the text analysis are groceries, services, transport of small goods, moving, manual labour, leisure activities (Table B-4). The category of leisure activities encompasses camping (n=56) and the transportation of goods to parks and other public spaces (n=68). The category of manual labour activities encompasses the transportation of gardening tools and plants (n=242) and do-it-yourself tools (n=59). The category of services includes deliveries made as part of the "*Cyclistes solidaires*" initiative (n=381), whereby individuals deliver groceries and meals to those who are unable to leave their homes due to the restrictions imposed by the Covid-19 pandemic. The category of transport encompasses the movement of various items, including small pieces of furniture (n=110), construction materials (n=155), general goods (n=108), and store pick-ups (n=186).

7.5.2 Generalised model results

In this section, we present the results of the three models and present the significant variables globally and for each city.

Table 7.6 Results for Model 1, Model 2 and Model 3

	Model 1			Model 2			Model 3		
AIC	1092.6			768.6			281.7		
	Estimate	e^x	p value	Estimate	e^x	p value	Estimate	e^x	p value
Intercept	4.57	97	1.27E-05***	4.49	89	< 2e-16 ***	-20.72	0	0.3216
Predictors									
Town	-0.37	0.69	0.66	-		-	-		-
Residential zoning proportion (CUBF_1)	0.51	1.67	0.0225 *	0.26	1.30	0.001 **	-0.08	0.92	0.9323
Manufacturing zoning proportion (CUBF_3)	0.14	1.15	0.3887	-0.02	0.98	0.915	4.17	64.72	0.3548
Commercial zoning proportion (CUBF_5)	1.14	3.13	1.25E-05 ***	2.19	8.94	5.69e-06 ***	0.62	1.86	0.4406
Services zoning proportion (CUBF_6)	-0.17	0.84	0.5316	-0.33	0.72	0.369	-9.48	0.00	0.0313 *
Population density (pop_density)	-0.10	0.90	0.6804	-0.05	0.95	0.848	-9.01	0.00	0.4885
Median income (median_income)	0.08	1.08	0.7018	0.26	1.30	0.292	-0.95	0.39	0.1386
Unemployment rate (unemployed_rate)	-0.55	0.58	0.0249 *	-0.26	0.77	0.496	-0.40	0.67	0.3367
Car possession per household (hh_car)	0.38	1.46	0.0229 *	0.67	1.95	0.002 **	0.32	1.38	0.1834
Significance levels: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1									

The intercept of each model is the log count of the expected number of trailer loans when all predictors are at zero. This means that for model 1, the expected number of trailer loans is 97, 89 for model 2 and 0 for model 3. For Model 3, the baseline count (intercept) does not contribute to the explanation of the model, which explains the null result for the intercept. However, an AIC of

281.7 suggests that the model is well-fitted to the data. The fact that the Brussels dataset contains less data than the Montreal dataset may also contribute to this result.

Model 1 has four significant predictors, which are the proportion of residential zoning, the proportion of commercial zoning, the unemployment rate and finally the number of cars per household. A one unit increase in the proportion of residential zoning is associated with a 66% $100(e^{0.51} - 1)$ increase in bike trailer loans. In the same way, a one-unit increase in the proportion of commercial zoning is associated with a 213% increase on bike trailer loans. These two results combine could indicate that in order to increase the number of trailer loans, the location of trailers should be in highly residential areas but near freight generating places, such as commercial streets or buildings. When it comes to the predictor unemployment rate, the association is negative, meaning that an unemployment increase would yield a 42.3 % decrease in bike trailer loans. Population areas with income stability are most likely to explain de success of trailers. Populations with higher levels of unemployment tend to have more digital, social and mental constraints and barriers to use this type of mobility solutions. Interestingly, areas with higher proportions of car possession are associated with a 45.5% increase in trailer loans. Combined with the previous result of the high residential area, it could mean that residents are shifting from cars to bike trailers to transport their smaller goods. This is also coherent with the different reasons specified by the users of the service for both Montreal and Brussels.

Model 2, based only on the data of the city of Montreal, has three significant predictors. Again, the proportion of residential area as well as the proportion of commercial activities are statistically significant. A one-unit increase for residential and commercial yields a 26.07% and 219.37% increase in bike trailer loans, respectively. The car possession predictor is also statistically significant, with a 95.98% increase for a one-unit increase for the predictor.

Model 3 is based only on the data of the city of Brussels and only presents one significant predictor, which is the proportion of services around the trailer depot. In Model 3, service zoning has a negative impact on the amount of trailer loans. This could hint that in Brussels, some trailers which are in zones with a high proportion of service should be relocated to other areas. Currently, many trailers are located in service areas such as public libraries, militant spaces and alternative supermarkets.

7.5.3 Clustering results

Table 7.7 presents the characteristics of the four clusters that were found.

Table 7.7 Clustering results by category of indicators

	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Accessibility indicators				
Distance to subway or tram (meters)	873.82	841.02	310.20	565.87
Distance to nearest bike-sharing station (meters)	129.47	151.95	217.44	187.03
Distance to bike network (meters)	111.38	124.88	158.38	98.25
Distance to car sharing station (meters)	190.11	229.46	273.86	223.46
Distance to train station (meters)	1522.61	1893.60	885.05	1762.26
Distance to bus station (meters)	98.33	102.86	266.25	171.06
Network indicator				
Number of trailers within 1 km	8.14	4.88	3.83	3.89
Operational indicators				
Mean distance traveled by the trailer (km)	11.16	11.39	14.42	30.47
Mean loan time of the trailer (minutes)	321.67 (~ 5 hours)	1261.02 (~ 21 hours)	920.59 (~ 15 hours)	4474.89 (~ 74 hours)
Socio-demographic indicators				
Population density	8,832.31	9,286.01	1,808.55	5,197.21
Median taxable income (in $CAD)	36,878.39	35,624.31	30,382.28	32,637.09
Household age	38.36	38.93	35.92	38.40
Household size	1.93	1.90	2.187	1.82
Car possession per household	0.67	0.62	0.41	0.49
Unemployment rate	8.15	10.11	24.66	13.18

Cluster 1 has the shortest distances to bike-sharing, car-sharing, and bus stations but is moderately farther from tram/subway or train stations. Cluster 2 is close to bus stations and moderately close to other transport, but farther from train stations. Cluster 3 is nearest to subway/tram and train stations but less accessible to bike-sharing, car-sharing, and bus stations. Cluster 4 has high accessibility to bike-sharing, moderate access to subways, car-sharing, and buses, but low access to train stations. It features a balanced mix of trailers from Montreal and Brussels, reflecting shared characteristics in accessibility and other factors (Figure 7.3, left).

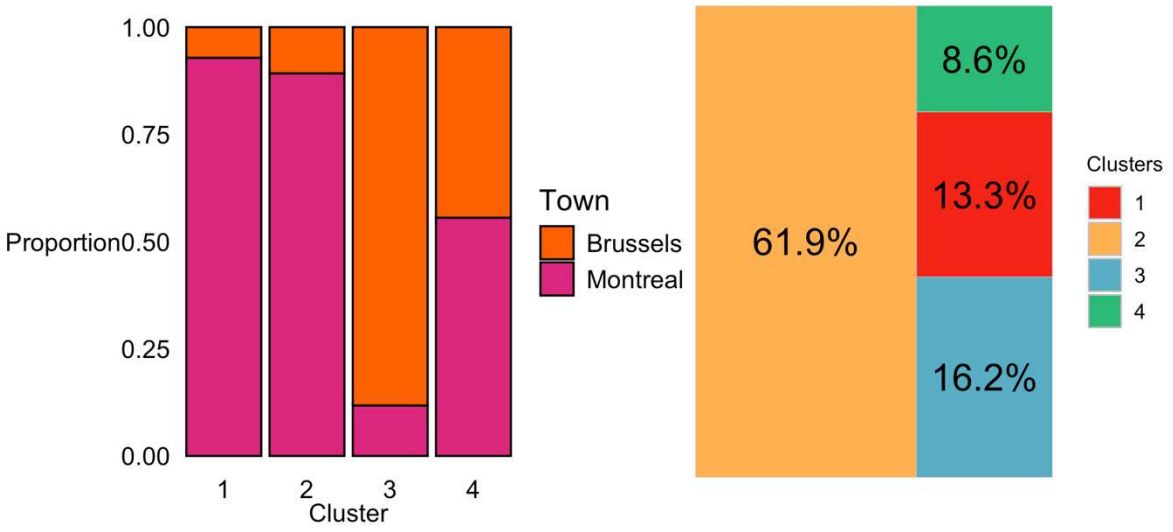


Figure 7.3 Proportion of each city within clusters (left) and proportion of each cluster (right)

Cluster 1 has the highest trailer density, with users borrowing trailers for short trips and brief periods, suggesting use for local tasks. Cluster 2 has a moderate number of trailers, similar travel distances to Cluster 1, but longer borrowing periods, indicating extended use. Cluster 3 has fewer trailers but involves longer trips and moderate loan periods, pointing to more deliberate, extended use. Cluster 4, with the fewest trailers, shows the longest trips and borrowing periods, often for leisure or relocation purposes. Cluster 1 is a high-density area with small households, moderate car ownership, and low unemployment. Cluster 2 is similarly dense and moderately affluent, with a lower car ownership rate, older population, and higher unemployment. Cluster 3 has a younger, lower-density population, larger households, and low car ownership. Cluster 4 is moderately dense

with middle-income, small households, moderate car ownership, and high unemployment, indicating some economic instability. Figure 7.4 compares all variables across clusters.

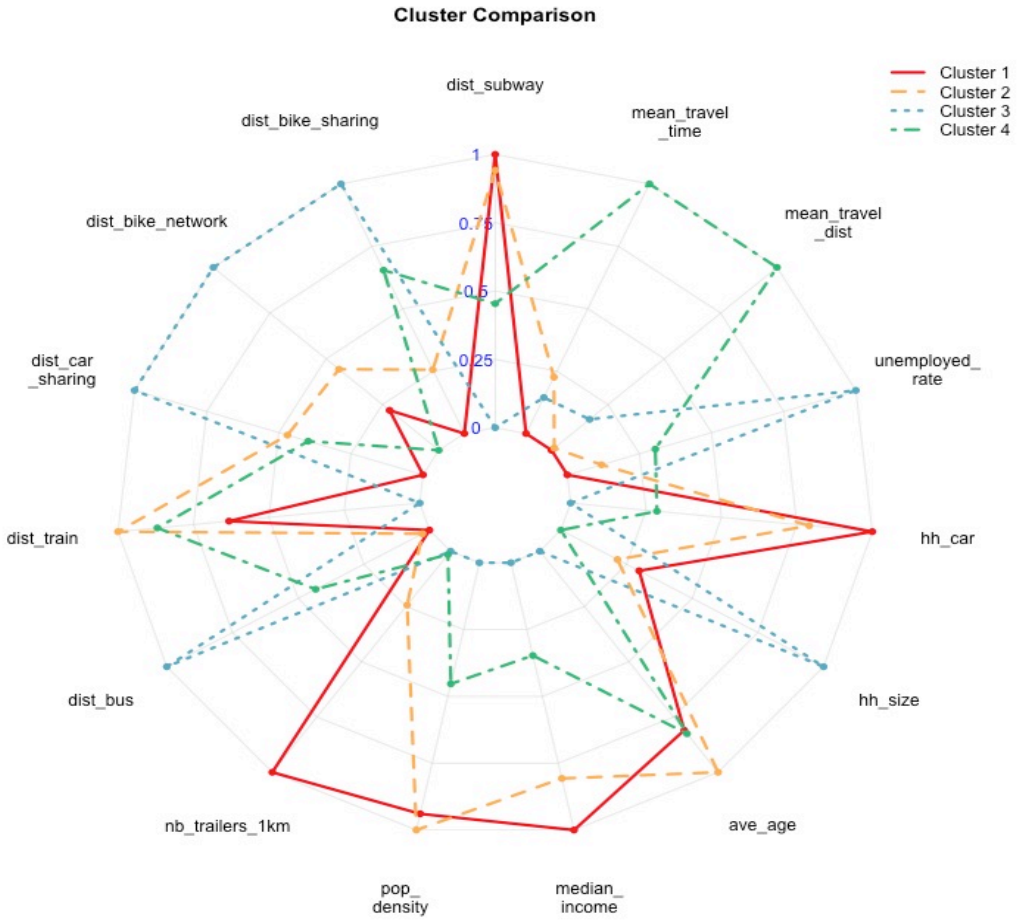


Figure 7.4 Comparison between clusters

Figure 7.6 and Figure 7.7 show the localisations of clusters results for both Montreal and Brussels. The results from the cluster analysis reveal how the two implementation strategies from operators *Remorquable* and *LocoMotion* vary. In Montreal, the chosen implementation strategy for trailers is to create a strong network, with a high density of trailers. This strategy is the same as that used for shared bikes (*Bixi*). One of the main advantages of this strategy is to increase the visibility of the initiative and to use the neighbourhood propagation effect to develop the bike trailer sharing initiative (Figure 7.5). While new members joined the initiative for each year, the strongest year

was 2022. 2023 marks a slowing down in the adhesion of new members. Figure 7.5 shows that the propagation of new members is concentrated in the central neighbourhoods of Montreal, almost copying the orange and green lines of the subway (see Figure 7.6for subway lines). When linked to the clustering results (Table 7.7,Figure 7.6 andFigure 7.7), clusters C1 appears to be highly linked with new adhesions in the system, suggesting that trailers in C1 can be a response to the new demand by new members in the system.

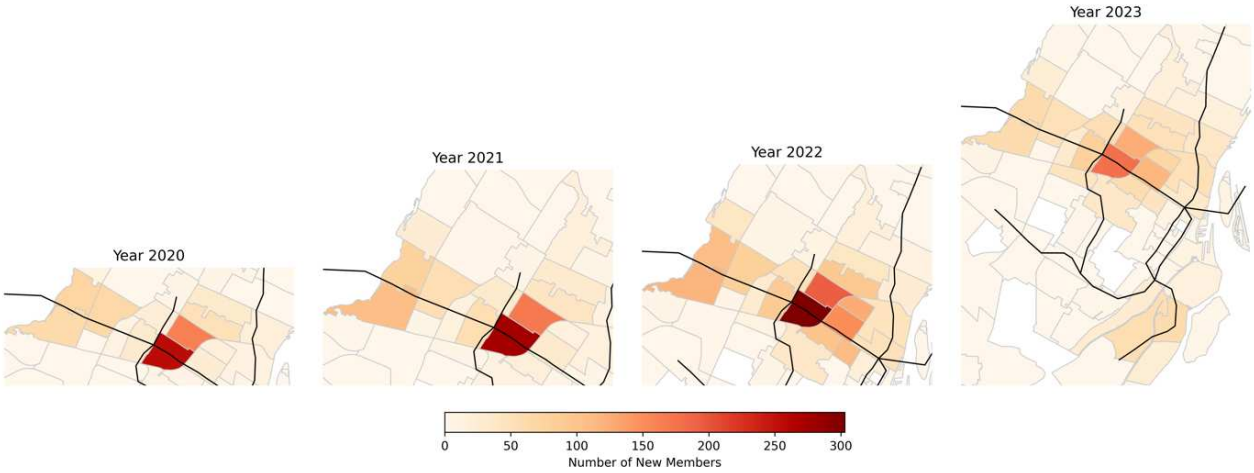


Figure 7.5 Propagation effect in Montreal

For the city of Brussels, the implementation strategy for the trailers is different. The density of trailers is lower, and some parts of the city have almost none of them (notably the northeastern zone in Figure 7.7). The implantation strategy caters to a more professional clientele, with strategically chosen localizations. While cluster 2 (C2) is dominant in both cities, C1 is almost inexistent in Brussels and C3 inexistant in Montreal. In Brussels, C3 encompasses mostly the trailers located in the Brussels Pentagon, which is the historic part of the city. C3 also encompasses the 19th century suburbs. These two types of neighborhoods are characterized by mixed-use activities and less car accessibility. These characteristics cannot be found in Montreal, as there are no trailers available in the historic part of the city.

Cluster 2 trailers (Figure 7.6 and Figure 7.7) have the same localization logic between both cities which are characterized by areas with residential function, yet in Brussels these areas are more peripherical. In Brussels, most areas are mixed-use, with Saint-Josse being slightly less so and Evere being predominantly industrial.



Figure 7.6 Location of the trailers by clusters in Montreal (central part of Montreal)

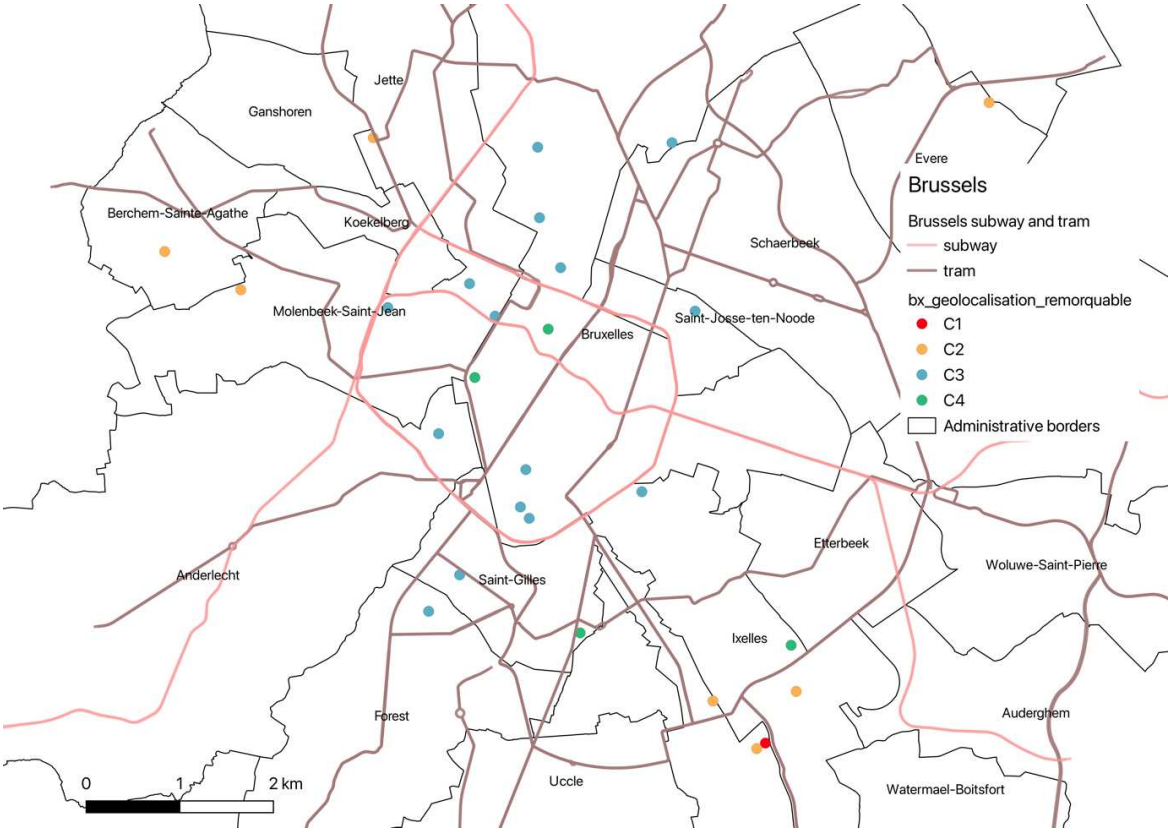


Figure 7.7 Location of the trailers by clusters in Brussels

7.6 Discussion and conclusion

7.6.1 Main findings

The first research question addressed failures and success factors of trailers uses. Residential and commercial zoning impact the loan of bike trailers the most. It can thus be suggested that these zonings are generating freight mobility or needs to transport goods by people. This result potentially underlines the need to include logistics of people both in the development of urban trailer network and, to a greater extent, in the urban planning. Conversely, a higher unemployment rate results in a decrease in trailer loans, indicating that populations with stable incomes are more likely to utilize this mobility option. This result is coherent with those from Barbour et al. (2019), whose study highlights that income (often correlated to unemployment) plays a significant role in bike sharing usage and modal substitution decisions. One of the issues that emerges from these findings is the possibility of a modal shift for the largest part of the population. Interestingly, another success factor is higher car ownership which is coherent with existing literature about

shared mobility. In their study, Bösehans et al. (2024) prove that the variables which increase the odds of being a shared mobility user include possessing a valid driver's license (+159 %), their result being coherent with the household car possession variable presented here. In this case, motorization rate and income have a medium correlation (0.37). Surprisingly, while shared bike trailers aim to be affordable the network is mainly located in residential areas characterized with high income. The second research question aims to compare different uses of bike trailers between Montreal and Brussels. By conducting a cluster analysis, we identify four distinct patterns of trailer usage. One interesting finding is that trailers usage for Cluster 4 are common for both cities, nevertheless cluster 4 represents the fewest number of trailers. A possible explanation for this might be that trailers are here seen as a cheaper alternative for cars to leisure and house moving purposes. Another important finding is that Montreal has more local loans with mainly short to medium time of borrowing (cluster 1 and 2) while Brussels has longer trips and moderate to long trips which perhaps show that trailers are mainly used as an alternative to car (cluster 3). This means that there is not just one type of consumer logistics, but several, a further study with more focus on these usage patterns is therefore suggested. Finally, descriptive results highlight with the nature of loans, the time of use and the user's registration type how the usage are surprisingly not only linked with consumption directly. Together these results provide important insights into the different patterns of freight with non-professional uses and enhance the potential for shared bicycle trailers to be a sustainable mode for households as underlined by previous research on cargo bikes (Glachant & De Séjournet, 2024). The weekly periods of use diverge; if we understand the weekend as a period that is mainly not reserved for work, then we could conclude that use in Montreal is mainly for leisure, whereas in Brussels it is more around professional use. In both cases, uses generated by households indicate that cargo bikes are potential new and more sustainable vehicles for these types of trips: house moving, gardening, construction. It is also a potential vehicle for testing the cargo bike and trailer before adoption through purchase beyond the professional fleet, construction professionals or households.

7.6.2 Limits

Even though the variables included in both the generalized model and the clustering method try to explain as many facets of the direct environment, more variables could be included, such as the safety aspects (presence of street lightning, trailer visibility from the street etc.). Moreover, the georeferencing the trailer depots is sometimes difficult and approximative. Some trailers are

geolocated on a main street when their exact position is in the back alley. This can lead to some inaccuracy within the two main datasets. The purpose of the two trailer initiatives is to provide member with a service that remains niche and emerging, especially when compared to establish micromobility services (i.e. shared bike services such as *Bixi* and *Villo*). This form of non-commercial micromobility service is in the minority in the landscape of micromobility operators in both countries. Because of this, generalization of results is limited., due to the emerging and innovative nature of the trailer loan initiatives, identifying underutilized trailers can be difficult and not as straightforward as for more established micromobility services.

7.7 Conclusion

Multiple forms of cycling vehicles have great potential to be the vehicles for tomorrow mobility for private transportation of goods. This article explains the success or failure factors linked to the use of shared bike trailers can be explained by through this article by a model based on geographic and socio-demographic variables. Then a clustering analysis provides a comparison between two case studies between Montreal and Brussels. Our results demonstrate the influence of the urban geographical environment on the success of trailers, indicating the importance of considering this factor in the planning and development of these services to ensure the success of this service. Through various patterns of use, we found that shared bike trailers can also represent a potential modal shift when an individual wishes to transport their goods independently. This leads us to consider a potential cultural change in household logistics or private goods transportation. These results illustrate how we can also consider the development of urban logistics by taking into account the resources available to consumers. Indeed, these results provide perspectives about decarbonization of household trips movement while the importance of household freight is underestimated (Beckers & Cant, 2023). According to these results, policymakers should make cycling infrastructures already adapted to different bikes dimensions which are transporting volumes. They should also ensure the accessibility of such services in order to guarantee their democratization. Then, the concrete application of this study for micromobility services is the importance of trailer depot location. This could be added to development from shared trailers services operators of two strategy of shared trailers development. To improve the results, more research is needed, especially to consider the implication of members of such initiatives and the motives of use of such non-commercial services.

CHAPITRE 8 DISCUSSION GÉNÉRALE

Les travaux effectués dans cette thèse mettent en évidence que l'utilisation des vélos-cargos représente une alternative viable aux modes motorisés dans le contexte de la logistique urbaine. Cependant, leur intégration, leur déploiement et leur mise à l'échelle dépendent fortement du contexte local, soulignant ainsi la nécessité d'une approche adaptée aux spécificités territoriales.

8.1 Synthèse des principaux résultats

Les recherches menées dans le cadre de cette thèse ont permis d'évaluer le potentiel des vélos-cargos et d'une autre solution de micromobilité pour la logistique urbaine, en identifiant à la fois leurs avantages et les défis liés à leur déploiement. Elles répondent aux objectifs définis à partir de la problématique initiale, en s'appuyant sur des analyses empiriques et méthodologiques adaptées à divers contextes urbains ainsi qu'aux données accessibles tout au long de ces travaux de thèse.

Tout d'abord, la viabilité des vélos-cargos en tant que mode de livraison à part entière a été démontrée à travers l'étude de l'initiative de livraison mise en place à Montréal durant la pandémie de Covid-19 (article 1). L'analyse quantitative des 6 700 livraisons effectuées révèle que le succès de ce mode de transport repose sur plusieurs facteurs, notamment la densité urbaine, les caractéristiques sociodémographiques des clients et la mise en place de stratégies de communication adaptées. Ces résultats confirment que les vélos-cargos peuvent s'intégrer efficacement aux systèmes de livraison du dernier kilomètre, en particulier dans un contexte de forte demande où les services conventionnels sont saturés.

Par la suite, une analyse approfondie des défis opérationnels et infrastructurels liés à l'usage des vélos-cargos en logistique urbaine a mis en évidence plusieurs contraintes (article 2). L'étude des infrastructures cyclables montre que les livreurs privilégient les aménagements séparés et bien entretenus, mais qu'ils doivent souvent adapter leur itinéraire en fonction des conditions météorologiques et de la qualité du réseau cyclable. De plus, le stationnement des vélos-cargos demeure un enjeu, car le manque d'espaces dédiés entraîne des pratiques improvisées pouvant impacter l'efficacité des livraisons. Ces observations soulignent la nécessité d'améliorations au niveau des infrastructures et d'une meilleure intégration des vélos-cargos dans les réglementations urbaines.

L'évaluation du potentiel des vélos-cargos au-delà des métropoles a permis d'identifier les conditions favorables à leur déploiement dans les villes moyennes (article 3). Grâce à une approche multicritère combinant des données sur la densité urbaine, les infrastructures cyclables et les flux commerciaux, il a été possible de classer les villes selon leur niveau de compatibilité avec ce mode de livraison. Les résultats montrent que, bien que ces territoires présentent des opportunités intéressantes, le manque d'infrastructures adaptées et la dispersion des flux commerciaux peuvent constituer des obstacles à une adoption massive. Cette analyse offre une première base méthodologique pour accompagner les municipalités de taille intermédiaire souhaitant intégrer les vélos-cargos dans leurs stratégies de logistique urbaine durable.

Enfin, l'exploration de solutions complémentaires à l'image des remorques à vélo partagées a mis en lumière leur potentiel pour la logistique des ménages (article 4). L'étude comparant Montréal et Bruxelles révèle que l'adoption de ces services est fortement influencée par la configuration urbaine et les besoins spécifiques des utilisateurs. Ces remorques sont principalement employées pour des usages ponctuels, tels que le transport de courses alimentaires, d'objets encombrants ou de matériel de bricolage. Toutefois, leur succès repose sur une implantation stratégique à proximité des zones résidentielles et commerciales. Ces résultats contribuent à élargir la réflexion sur la micromobilité en tant que solution de transport durable et complémentaire aux vélos-cargos pour les ménages.

Dans l'ensemble, ces travaux démontrent que les vélos-cargos et solutions de micromobilité associées constituent des alternatives viables aux modes de transport motorisés pour la logistique urbaine. Cependant, leur pleine intégration nécessite une planification à la fois par les villes et les transporteurs, notamment pour la mise à l'échelle, ainsi que des ajustements au niveau de la réglementation pour garantir leur efficacité et leur pérennité dans différents contextes urbains.

8.2 Cohérence et divergence des résultats avec la littérature scientifique

D'une part, les résultats obtenus sont en grande partie cohérents avec ceux observés dans la littérature scientifique. Plusieurs facteurs ont été identifiés comme déterminants pour le succès des initiatives de cyclologistique, notamment la densité de population (articles 1, 3 et 4), que l'on retrouve dans de nombreuses études qui intègrent des vélos-cargos (Choubassi, 2015; Gonzalez-Calderon et al., 2022; Hofmann et al., 2018; Llorca & Moeckel, 2020). Deux autres facteurs déterminants sont la configuration spatiale des villes (articles 3 et 4), ainsi que la présence d'une

mixité des usages du sol, notamment par la proximité entre les zones commerciales et résidentielles (articles 1, 3 et 4), ce qui est cohérent avec l'étude réalisée à New-York (Yang et al., 2024). Par ailleurs, la flexibilité et l'adaptabilité des modèles logistiques apparaissent comme des atouts majeurs (articles 1 et, dans une certaine mesure, article 3), point particulièrement mis en avant dans les études de (Choubassi et al., 2016; Elbert & Friedrich, 2020; Katsela et al., 2021). Cette flexibilité permet la mise en place de projets pilotes à coûts réduits et limitant ainsi les risques financiers et organisationnels liés à leur implantation. L'initiative spontanée de livraison par vélo-cargo mise en place à Montréal durant la pandémie de Covid-19 illustre comment un contexte exceptionnel peut favoriser une adoption rapide de cette solution, tout en révélant certaines de ses limites (article 1), notamment sur la communication et la visibilité de telles initiatives.

Cependant, les résultats obtenus divergent sur l'usage des infrastructures cyclables lors des activités de livraison (article 2). Là où l'étude de Dalla Chiara et al. (2023) démontre une forte utilisation des trottoirs pour la circulation et le stationnement, les résultats démontrent qu'à Montréal, les livreurs essaient d'éviter les trottoirs et préfèrent l'utilisation de pistes cyclables. Cette différence peut être imputable à la culture (ou manque de) cycliste présente dans les différentes villes. L'étude menée à Montréal montre que l'adéquation entre les infrastructures cyclables et les itinéraires empruntés par les livreurs influence directement leur efficacité et leur sécurité (article 2). Par ailleurs, l'attitude des livreurs envers ces infrastructures varie selon les conditions climatiques et les infrastructures présentes, ce qui souligne la nécessité d'adapter les aménagements urbains pour maximiser leur efficacité.

8.3 Transférabilité des apprentissages

Les apprentissages issus de l'article 1, réalisé dans un contexte exceptionnel de crise sanitaire, peuvent être transférés à d'autres projets pilotes, notamment en matière d'adoption rapide et d'organisation logistique flexible. Ces enseignements permettent d'anticiper les conditions favorables à une transition efficace vers des solutions de cyclologistique dans des situations d'urgence ou de forte demande ponctuelle.

En parallèle, les initiatives de partage de remorques en libre-service démontrent que l'acceptation de la micromobilité pour le transport de marchandises ne se limite pas aux professionnels, mais concerne également les ménages (article 4). Ce constat souligne le potentiel d'expansion du concept, en particulier dans les zones urbaines où la voiture individuelle reste fortement ancrée

dans les habitudes de déplacement, et/ou pour lesquelles il n'existe pas beaucoup d'alternatives de déplacement grâce au transport public. En facilitant le transport de biens pour les ménages, ces solutions permettent de réduire la dépendance aux véhicules motorisés et d'encourager une transition vers une mobilité urbaine plus durable.

8.4 Méthodes et limites des méthodes

Les méthodologies employées dans cette thèse combinent plusieurs approches innovantes, notamment l'analyse multi-niveaux, les méthodes de clustering et l'intégration de données ouvertes. Ces méthodes se sont révélées particulièrement pertinentes pour comprendre les dynamiques complexes de la cyclologistique. L'analyse spatiale appliquée aux villes moyennes, par exemple, a permis de catégoriser les territoires selon leur propension à accueillir des initiatives de cyclologistique, en tenant compte de multiples critères tels que la densité de population, l'infrastructure cyclable et les conditions climatiques (article 3).

Cependant, ces méthodes présentent certaines limites. L'absence de données précises sur le volume exact des marchandises transportées par les vélos-cargos rend difficile une comparaison directe avec d'autres modes de transport. De plus, bien que l'analyse multi-niveaux ait permis d'identifier des facteurs déterminants dans l'initiative montréalaise, la temporalité restreinte de l'étude empêche d'en tirer des conclusions généralisables à long terme (article 1). Enfin, l'approche qualitative basée sur des entretiens avec les livreurs apporte des éléments riches mais subjectifs. Ces résultats gagneraient à être complétés par des analyses quantitatives plus poussées et par un échantillon plus large, incluant des livreurs évoluant dans d'autres contextes géographiques (article 2).

Les résultats obtenus montrent que les vélos-cargos peuvent être intégrés de manière efficace dans les chaînes logistiques urbaines, à condition que des aménagements spécifiques en infrastructures soient réalisés et que des réglementations adaptées émergent à l'avenir. Dans les grandes métropoles comme Montréal, leur efficacité est maximisée lorsqu'ils sont associés à des micro-hubs et bénéficient d'un réseau cyclable continu, large et fiable en toute saison (article 2). En revanche, dans les villes moyennes, leur succès dépend davantage de la densité de population et des flux commerciaux locaux (article 3), en raison du manque d'infrastructures cyclables adaptées.

Une des limites majeures réside dans la variabilité des contextes urbains. Les conditions hivernales au Québec posent des défis spécifiques aux livreurs à vélo-cargo, nécessitant des adaptations

techniques et organisationnelles pour garantir leur viabilité toute l'année (article 2). De plus, les résultats obtenus en période de pandémie doivent être interprétés avec prudence, car les dynamiques de consommation et de livraison étaient fortement perturbées par les restrictions sanitaires (article 1).

Les enseignements issus de cette thèse fournissent plusieurs pistes de réflexion pour les décideurs publics et les acteurs privés de la logistique urbaine. Premièrement, ils soulignent l'importance d'une planification urbaine intégrée qui prenne en compte les besoins spécifiques des vélos-cargos. Ensuite, ils mettent en évidence la nécessité de renforcer les infrastructures cyclables et d'adopter des politiques de soutien à la cyclologistique pour encourager son déploiement à grande échelle. Cette discussion met en lumière la diversité des approches possibles pour intégrer les vélos-cargos et la micromobilité dans la logistique urbaine. Si les résultats de cette thèse confirment leur pertinence en tant qu'alternative durable, ils révèlent également la nécessité d'une adaptation fine aux spécificités locales. Les défis liés aux infrastructures et aux conditions climatiques doivent être pris en compte pour maximiser leur impact. En conclusion, cette recherche ouvre des pistes pour une planification plus intégrée des modes de transport actifs en logistique urbaine, tout en posant les bases de réflexions futures sur leur déploiement à plus grande échelle.

CHAPITRE 9 CONCLUSION ET PERSPECTIVES

Ce chapitre présente les contributions principales de cette thèse (9.1) et limites (9.2) des différents travaux menés au cours de ce parcours de thèse. La dernière section présente les perspectives envisageables dans le domaine de la cyclologistique pour des recherches futures (9.3).

9.1 Contributions de cette thèse

Les travaux de cette thèse visent à contribuer à l'étude de la cyclologistique en milieu urbain en proposant des approches méthodologiques et quantitatives pour évaluer le potentiel de l'utilisation des vélos-cargos.

Une des contributions de cette thèse consiste en l'analyse des mutations de la logistique urbaine engendrées par la pandémie de Covid-19. L'étude des initiatives mises en place à Montréal révèle que la crise sanitaire a agi comme un catalyseur pour l'adoption des vélos-cargos, en raison de l'augmentation exponentielle des livraisons à domicile et des contraintes imposées aux modes de transport traditionnels. En recourant à une modélisation multi-niveaux, il est possible d'identifier les facteurs déterminants du succès de ces initiatives, notamment la densité de population, les caractéristiques socio-démographiques des quartiers desservis et l'efficacité des stratégies de communication mises en place pour promouvoir ces services. Cette approche permet d'éclairer les conditions nécessaires à une pérennisation des initiatives de livraison par vélo-cargo au-delà des périodes de crise.

Par ailleurs, l'article 2 permet de mettre en évidence l'impact des infrastructures urbaines sur les conditions de travail des livraisons par vélo-cargo. Elle souligne que la qualité et la continuité des pistes cyclables, la disponibilité des espaces de stationnement et l'adaptation des infrastructures aux conditions météorologiques influencent directement l'attrait pour les personnes effectuant les livraisons et la performance de ces solutions logistiques. L'analyse des préférences des livreurs, fondée sur des observations empiriques et des enquêtes de terrain, permet de mieux comprendre les stratégies qu'ils adoptent pour optimiser leurs trajets et sécuriser leurs arrêts de livraison. En ce sens, la thèse contribue à une meilleure planification des aménagements urbains en tenant compte des besoins spécifiques des opérateurs de cyclologistique. De plus, peu d'études couvrent des terrains hivernaux, ce qui permet de contribuer à la littérature sur le sujet de manière empirique.

Un des partis pris de ces travaux de thèse est une utilisation accrue des données ouvertes. En s'appuyant fortement sur ce genre de données, il est possible de proposer des méthodologies réplicables et adaptables à divers contextes urbains (article 3, article 4), facilitant ainsi la comparaison entre différentes villes. L'utilisation de données ouvertes permet non seulement d'assurer une plus grande transparence dans l'évaluation du potentiel des vélos-cargos, mais aussi de démocratiser l'accès à des outils d'analyse avancés pour les chercheurs, les urbanistes et les décideurs publics. Cette approche contribue à réduire la dépendance aux données propriétaires, souvent inaccessibles ou limitées aux acteurs privés, et favorise le développement d'une recherche collaborative et ouverte sur la logistique urbaine durable.

Finalement, les travaux en collaboration avec Bruxelles (article 4) permettent d'ouvrir la réflexion sur l'intégration de solutions de micromobilité pour la logistique des ménages, représentant ainsi un transfert de connaissance et d'application entre l'utilisation des vélos-cargos dans un cadre commercial vers un cadre privé. L'analyse des conditions d'adoption des remorques à vélo met en évidence l'influence des facteurs socio-économiques, du type de zonage urbain et de l'accessibilité aux infrastructures de transport. En comparant différentes stratégies de déploiement dans plusieurs villes, elle met en évidence les opportunités et les obstacles liés à ces solutions émergentes.

À partir des contributions de la thèse, il est possible de se projeter dans les perspectives possibles, qui seront détaillées à la section 9.3 (Figure 9.1).

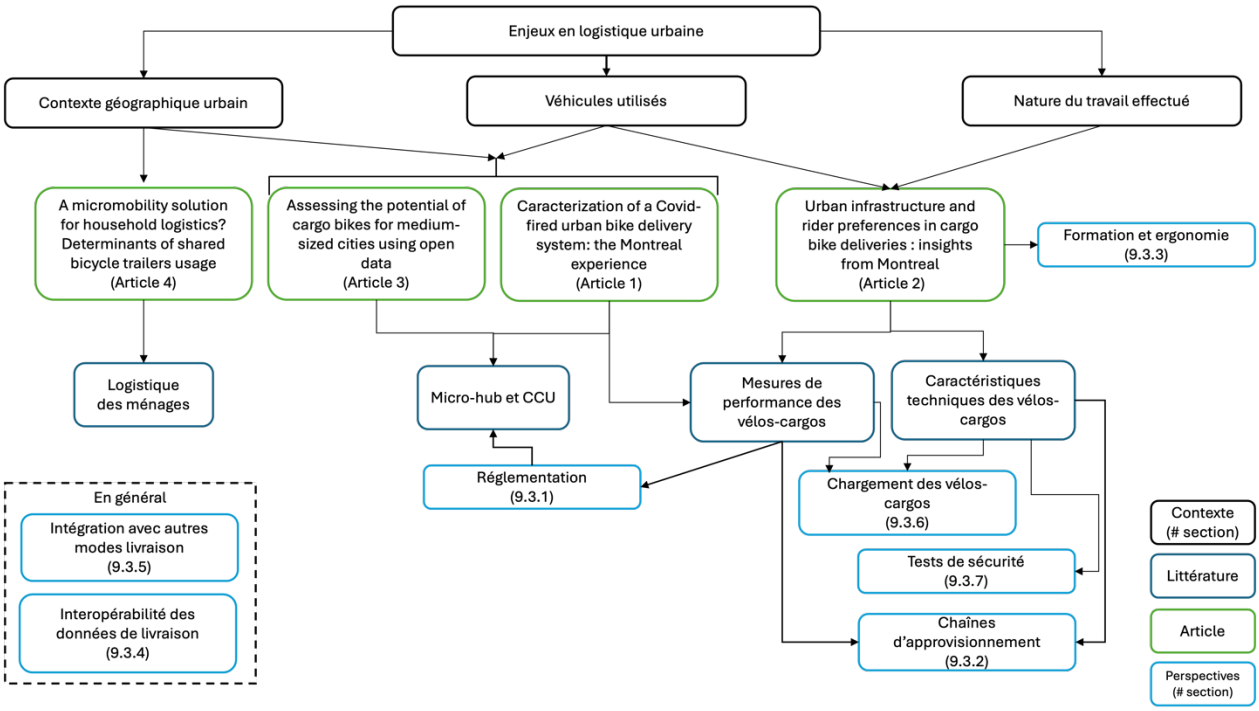


Figure 9.1 Synthèse des contributions et liens avec les perspectives

9.2 Limites des travaux

Bien que cette thèse apporte une contribution à la compréhension du potentiel des vélos-cargos dans la logistique urbaine, certaines limites doivent être soulignées afin d'en préciser la portée et d'identifier les axes d'approfondissement possibles. Ces limites concernent principalement la généralisation des résultats à d'autres contextes urbains, la nature des données utilisées, l'intégration des vélos-cargos avec d'autres modes de transport, ainsi que la prise en compte des préférences des consommateurs et de l'acceptabilité sociale de ces solutions de livraison.

Tout d'abord, la généralisation des résultats à d'autres contextes urbains est une problématique importante. Les études effectuées lors de cette thèse se concentrent majoritairement sur le territoire de Montréal et dans une moindre mesure sur le reste du Québec à travers l'article sur les villes moyennes (article 3). Ce choix limite la transférabilité des conclusions à d'autres villes dont les caractéristiques urbaines, économiques et sociales diffèrent de celles d'une grande agglomération, dans laquelle la culture du vélo commence à être établie.

Les travaux de cette thèse sont le résultat d'un parti pris de se baser très fortement sur des données ouvertes, ainsi que sur des outils d'analyse spatiale (article 3 et article 4). Bien que ces sources

permettent d'obtenir un portrait ou bien de faire des approximations, elles ne peuvent se substituer à des données de flux de marchandises, qui appartiennent souvent aux entreprises privées. Certaines variables essentielles, comme les volumes exacts de marchandises transportées, les itinéraires précis suivis par les coursiers ou encore leurs interactions avec les autres usagers de la route, ne sont pas toujours accessibles ou suffisamment détaillées. L'utilisation de plateformes comme Strava (article 2) ou de sondages auprès des usagers (article 2) introduit également un biais de sélection, car ces données ne couvrent qu'une partie des acteurs de la cyclologistique et ne reflètent pas nécessairement l'ensemble des pratiques existantes.

Tous les travaux présentés précédemment considèrent le vélo-cargo comme mode de transport unique, aucune attention n'est portée à l'intégration de ce dernier avec d'autres modes de transport, comme les casiers de livraison, le transport en commun ou des vans (électriques ou non). De même, le rôle du micro-hub logistique est considéré comme acquis et n'est pas considéré au sein des études. Par ailleurs, la cohabitation entre les vélos-cargos et les véhicules motorisés, ainsi que les conflits d'usage de la voirie, sont des problématiques qui restent peu analysées malgré leur impact potentiel sur l'efficacité des opérations.

Tous les travaux présentés sont du côté des services logistique, les préférences des consommateurs ou l'acceptabilité sociale des vélos-cargos n'est pas un aspect qui a été étudié. En effet, la sensibilisation du public aux bénéfices environnementaux de ces modes de livraison et leur influence sur le choix des consommateurs mériteraient une analyse plus poussée, notamment en ce qui concerne la disposition des clients à payer pour un service de livraison plus durable.

Pour conclure, bien que la thèse offre une analyse du potentiel des vélos-cargos et des infrastructures de cyclologistique, plusieurs limites subsistent. L'élargissement des études à d'autres contextes urbains, ainsi qu'une exploration plus approfondie des interactions avec d'autres modes de transport et des attentes des usagers permettraient de continuer les travaux. D'autres pistes de réflexion sont aussi avancées à la section 9.3.

9.3 Perspectives en cyclologistique

Cette section vise à présenter les différentes perspectives qui pourraient être envisagées pour compléter les travaux sur la cyclologistique. Les sections 9.3.1 et 9.3.2 sont des perspectives d'ordre stratégique, tandis que les sections 9.3.3, 9.3.4 et 9.3.5 présentent des perspectives d'ordre tactique. Les perspectives opérationnelles sont présentées aux sections 9.3.6 et 9.3.7.

9.3.1 Réglementation

Au Québec, le développement de la cyclologistique s'est faite grâce aux efforts des transporteurs, de leurs partenaires comme Coop Carbone ou Jalon Montréal ainsi que des municipalités. Cependant, il n'existe pas encore de réglementation spécifique qui permettrait de favoriser l'intégration, le déploiement ou la mise à l'échelle de l'utilisation des vélos-cargos. Dans son projet de plan d'action pour la logistique urbaine, la ville de Montréal a identifié la mise en place de réglementation spécifique comme un de ses actions à mettre en place.

- Mise en place de zones réglementées

La mise en place de zones réglementées constitue un levier efficace pour encourager l'usage des vélos-cargos en milieu urbain, notamment à travers les zones à faibles émissions (ZFE). À Barcelone, l'introduction d'une ZFE a suscité une attitude globalement positive de la part des habitants (Oltra et al., 2021). Cette initiative a également favorisé le développement de deux projets pilotes de livraison par vélos-cargos, bien que l'un d'eux ait échoué dans le cas de la livraison de produits réfrigérés, en raison de contraintes logistiques spécifiques (Sochor et al., 2023). Toutefois, certains experts plaident en faveur d'une tarification à la congestion plutôt que de la mise en place de ZFE, arguant que ces dernières ne génèrent pas de revenus et qu'elles ne ciblent pas nécessairement les véhicules les plus polluants (Dooly & Trepat, 2020).

À Montréal, plusieurs secteurs pourraient être propices à l'implantation d'une ZFE. Le Vieux-Port, où la circulation est déjà restreinte durant certaines heures en période estivale, représente un candidat naturel. De même, les artères commerciales piétonnisées en été pourraient constituer des zones stratégiques pour une expérimentation progressive. Toutefois, afin de mieux anticiper et évaluer les impacts de telles mesures, tant sur la réduction des émissions que sur l'intégration des vélos-cargos dans la logistique urbaine, il serait pertinent de recourir à des approches de modélisation avancées. L'utilisation de la simulation multi-agents ou du jumeau numérique à l'échelle d'un quartier permettrait d'analyser différents scénarios avant une mise en œuvre à plus grande échelle, rendant ainsi la démarche plus robuste et adaptée aux spécificités locales.

- Écofiscalité

L'écofiscalité constitue un levier stratégique pour favoriser l'adoption des vélos-cargos au sein des flottes de livraison. Dans leur revue de la littérature sur les différents dispositifs d'incitation

financière à l'achat d'un vélo électrique, Nosratzadeh et al. (2025) démontrent que 75 % des programmes incitatifs s'appliquent à une échelle géographique restreinte et ciblent principalement des particuliers, plutôt que des entreprises. De plus, 39 % de ces programmes incluent les vélos-cargos électriques parmi les véhicules admissibles, mais, parmi ces derniers, seuls 25 % concernent des programmes nord-américains. Pour les particuliers, la présence d'incitatifs immédiats, tels qu'une exemption fiscale, accroît la probabilité d'opter pour un véhicule électrique plutôt qu'un véhicule thermique (Urrutia-Mosquera & Fábrega, 2021). Il serait donc pertinent pour les villes du Québec d'adopter une approche similaire en mettant en place des incitatifs financiers à l'achat de vélos-cargos non seulement pour les particuliers et les entreprises, mais également pour les travailleurs indépendants offrant des services (électricien, infirmière etc.).

9.3.2 Résilience de la chaîne d'approvisionnement des vélos-cargos

Dans leur rapport publié en 2020, l'organisme Jalon Montréal met en évidence la nécessité d'adapter les vélos-cargos utilisés pour la livraison aux conditions spécifiques du Québec, notamment aux rigueurs de l'hiver ainsi qu'à l'état parfois avancé de dégradation des chaussées (Jalon Montréal, 2020). Cette adaptation passe non seulement par des innovations techniques, mais également par la mise en place d'une chaîne d'approvisionnement solide, durable et locale pour ces véhicules. Selon une étude récente menée par MileBox et Coop Carbone sur la chaîne d'approvisionnement des vélos électriques, le Québec compte actuellement 22 manufacturiers de vélos, dont environ un tiers propose des vélos destinés aux entreprises (Coop Carbone & Milebox, 2024). Cette présence manufacturière offre un potentiel intéressant pour le développement de solutions adaptées aux besoins de la logistique urbaine durable. Si de nombreuses recherches se sont penchées sur l'intégration des vélos-cargos au sein des chaînes d'approvisionnement en général (Caggiani et al., 2021; Llorca & Moeckel, 2020; Nürnberg, 2019; Pelet et al., 2023; Robichet et al., 2022), plusieurs axes d'étude demeurent encore à approfondir. Parmi ceux-ci, l'analyse du vélo-cargo en tant que mode de livraison à part entière, l'optimisation de sa chaîne d'approvisionnement, sa modularité (voir section 9.3.6) ainsi que les enjeux liés à sa sécurité (voir section 9.3.7) constituent des pistes de recherche intéressantes. Ces perspectives s'avèrent d'autant plus pertinentes dans un contexte où la transition vers des modes de transport plus durables s'impose comme une priorité pour les acteurs du transport et de la logistique urbaine.

9.3.3 Formation des personnes chargées de la livraison

À la lumière des recherches menées, il n'existe pas, à proprement parler, de formation spécifique au Québec ou dans le reste du Canada pour les personnes effectuant des livraisons à l'aide de vélos-cargos. La seule initiative s'en approchant en matière de santé et sécurité est le rapport scientifique de l'IRSST sur l'essor des services de livraison à vélo et les enjeux de santé et sécurité des cyclistes commerciaux (Lachapelle et al., 2020). Plus récemment, Coop Carbone a mis en place un label de livraison durable (« Certification Livraison durable »), garantissant de bonnes conditions de travail ainsi qu'une formation en sécurité routière pour les opérateurs de vélos-cargos.

En Europe, la formation Safe LMD (*SafeLMD-Compétences Écologiques et de Sécurité Pour Les Travailleurs Dans Les Livraisons Urbaines Du Dernier Kilomètre à Vélo*) propose une formation gratuite aux livreurs à vélo(-cargo). Ce programme comprend cinq modules couvrant différents aspects : la logistique (ex. : types de marchandises et emballages), la sécurité routière (ex. : bases d'une conduite sécuritaire), les notions administratives liées au statut de travailleur autonome ainsi que des éléments techniques sur le fonctionnement du vélo. Toutefois, étant conçue pour un contexte européen, cette formation, bien que complète, ne traite pas de certaines spécificités comme l'équipement hivernal et la maintenance requise en conditions nordiques. Elle ne prend pas non plus en compte les compétences nécessaires pour gérer les situations de violences verbales, fréquentes dans les environnements où la culture cycliste demeure fragile. Enfin, il serait pertinent que les livreurs à vélo bénéficient d'une formation plus approfondie en ergonomie, notamment sur la posture à adopter sur leur vélo et lors de la manipulation des colis (levage, port, dépôt, etc.) (Figure 9.2), ainsi qu'en premiers soins.



Figure 9.2 Visualisation de la posture lors d'un porté par vision par ordinateur (module Yolo v7)

9.3.4 Interopérabilité des données de livraison

L'interopérabilité des données de transport constitue un levier fondamental pour optimiser l'intégration des vélos-cargos dans les flottes de livraison et favoriser la mutualisation des flux à partir de micros-hubs urbains. Ce concept s'inscrit dans le cadre plus large de l'Internet physique (« *Physical Internet* »), où l'échange standardisé et fluide des informations est essentiel pour améliorer l'efficacité logistique. En facilitant la communication entre les différents acteurs de la logistique urbaine (transporteurs, plateformes numériques, commerçants et collectivités), l'interopérabilité permettrait une utilisation optimisée des ressources de transport et une planification plus efficace des itinéraires (Ambra et al., 2019). Toutefois, cette interopérabilité demeure encore limitée, les systèmes de gestion des données opérant majoritairement de manière cloisonnée, freinant ainsi l'émergence de solutions logistiques véritablement collaboratives (Ambra et al., 2019). Une interconnexion efficace des systèmes d'information pourrait néanmoins faciliter l'intégration des vélos-cargos, en particulier pour la mutualisation des livraisons dans des secteurs urbains spécifiques, tels que les zones à forte congestion ou les rues piétonnières. Cette intégration pourrait s'appuyer sur des modèles de livraison en marque blanche, où l'identité du

prestataire de transport reste neutre, favorisant ainsi une approche mutualisée et flexible. Afin de mieux appréhender les bénéfices et les défis d'une telle mise en œuvre, il serait pertinent de développer un projet pilote impliquant plusieurs entreprises sur un périmètre géographique restreint, permettant ainsi d'évaluer les gains opérationnels, environnementaux et économiques d'une interopérabilité accrue des données de logistique urbaine.

9.3.5 Intégration des vélos-cargos avec d'autres modes de livraison

Les travaux de cette thèse portent sur les déterminants spécifiques aux vélos-cargos et aux remorques à vélo. Toutefois, l'intégration des vélos-cargos avec d'autres modes de livraison aurait également pu être envisagée. En particulier, les casiers de livraison constituent une solution complémentaire souvent associée à l'utilisation des vélos-cargos (Enthoven et al., 2020; Peppel et al., 2022; Rolf et al., 2023; Yang et al., 2024; L. Zhang et al., 2018), tandis que l'usage des drones, bien que plus marginal, fait l'objet de certaines considérations (Kunze, 2016; Serrano-Hernandez et al., 2021). Dans la littérature scientifique, l'intégration des vélos-cargos est principalement abordée sous l'angle de la recherche opérationnelle, notamment pour résoudre des problèmes de routage de véhicules à deux échelons (Enthoven et al., 2020) ou pour optimiser la planification des itinéraires et la localisation des casiers de livraison (Rolf et al., 2023). Ces travaux pourraient être enrichis par une approche plus proche de l'urbanisme et de la planification urbaine, intégrant des critères d'accessibilité, de sécurité et de désirabilité des emplacements des casiers de livraison, tels que détaillés dans les études de An et al. (2022), Iannaccone et al. (2021), Lachapelle et al. (2018) et Lemke et al. (2016). Par ailleurs, il serait pertinent d'examiner les effets d'un stationnement dynamique, où certaines plages horaires seraient réservées à un véhicule de réapprovisionnement des vélos-cargos, tandis que le reste du temps serait consacré au stationnement classique. Une telle mesure pourrait être particulièrement intéressante dans le contexte des nouveaux pôles de mobilité de la ville de Montréal. Enfin, l'intégration des vélos-cargos avec d'autres modes de livraison, notamment les casiers, contribuerait également à renforcer leur visibilité auprès des citoyens.

9.3.6 Chargement des vélos-cargos

D'ordre tactique, le chargement des vélos-cargos est un sujet d'intérêt, à la fois pour le monde de la recherche, tout comme pour les opérateurs. Étant donné la capacité limitée des vélos, il est primordial d'optimiser tout l'espace à disposition. Le terme « d'encapsulation » émerge, afin de

nommer les différentes pratiques qui seront nécessaires pour permettre un chargement des vélos-cargos le plus optimal possible.

- Encapsulation des colis

L'adéquation entre l'emballage et le volume du colis constitue un enjeu majeur. Trop souvent, les emballages sont disproportionnés par rapport aux objets transportés. Dans leur revue systématique de la littérature sur le taux de remplissage et la conception des emballages, Ahmad et al. (2022) soulignent que peu d'études se penchent sur ces questions, principalement en raison de la difficulté d'accès aux données. Les auteurs précisent également que les interventions en matière d'emballage prennent rarement en compte le domaine du transport et que leur impact reste peu étudié. Concernant le chargement des vélos-cargos, il serait pertinent de développer des modèles intégrant à la fois la masse et le volume des colis, tout en optimisant leur ordre de chargement afin de limiter la sur-manipulation, particulièrement coûteuse. À plus long terme, la diversification des types de vélos-cargos au sein des flottes permettrait d'adapter le choix du véhicule en fonction de ses caractéristiques de chargement (accès par le haut ou par l'arrière, capacité, maniabilité, etc.), de l'itinéraire à effectuer et des exigences ergonomiques pour les livreurs. Par exemple, cela éviterait le transport de boîtes très lourdes et compactes, telles que des archives gouvernementales, dans un caisson à chargement par le haut trop élevé par rapport à la taille du livreur. De même, pour les vélos-cargos qui ont un chargement de type attelage, le positionnement de la plus lourde masse a un impact sur la sécurité de la livraison (cet aspect sera détaillé à la section 9.3.7).

- Encapsulation des modules

Un autre aspect à considérer est l'encapsulation des modules afin d'accélérer le chargement des vélos-cargos, en particulier pour les remorques à attelage. L'utilisation de boîtes standardisées ou de conteneurs modulaires et compatibles pourrait constituer une solution prometteuse pour optimiser les performances des vélos-cargos. Parmi les études les plus complètes sur le sujet, celle d'Aiello et al. (2021) cherche à optimiser cette approche en tenant compte de la capacité de la batterie. Par ailleurs, certaines recherches proposent des spécifications d'ordre technique, mais sans se concentrer spécifiquement sur l'utilisation de modules de chargement (Assmann & Behrendt, 2017; Bogdanski et al., 2021).

9.3.7 Tests de sécurité

La littérature scientifique consacrée aux tests de sécurité des vélos-cargos demeure limitée, qu'ils soient conçus pour le transport de marchandises ou de personnes. Une étude portant sur l'adéquation entre la forme du vélo-cargo et la sécurité des cyclistes montre que le positionnement d'une charge à l'avant du vélo-cargo influence négativement la sécurité du cycliste sur le vélo, tandis que les vélos plus courts bénéficient d'un meilleur rayon de braquage dans les intersections (Paudel & Yap, 2024). Toutefois, cette étude se focalise sur des aspects purement techniques, tels que l'accélération, le freinage, le contournement d'obstacles ou encore le rayon de braquage, sans intégrer l'expérience des cyclistes ni leur interaction avec l'environnement bâti.

Par ailleurs, à notre connaissance, aucune méthode standardisée n'a été développée pour produire des résultats de tests de collision spécifiques aux vélos-cargos. En revanche, la littérature sur l'accidentologie des cyclistes est relativement abondante. Il serait ainsi pertinent de comparer les résultats obtenus en fonction des types de vélos (vélo classique, vélo-cargo, vélo à assistance électrique, vélo-cargo à assistance électrique, etc.), des profils d'usagers (cycliste récréatif, sportif, professionnel) et de la charge transportée (cycliste commercial avec remorque, cycliste récréatif avec remorque pour enfants), ainsi que d'autres configurations pertinentes. Néanmoins, le coût élevé de ce type d'études constitue un frein à leur mise en œuvre.

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ANNEXE A Article 3 : annexes

Cette annexe A correspond aux annexes du troisième article de cette thèse, présenté au chapitre six. Il s'agit du questionnaire de la méthode Delphi.

Section on Population

Population density (inhabitants/km²) is … for establishing a cycle logistics initiative.

1. Not at all important
2. Slightly important
3. Moderately important
4. Very important
5. Absolutely essential

The population growth rate (%/year) is … for establishing a cycle logistics initiative. The distribution of jobs (%/sector) is … for establishing a cycle logistics initiative.

Section on Population and Goods Flows

Population flows, when known, are … to consider for establishing a cycle logistics initiative. Goods flows, when known, are … to consider for establishing a cycle logistics initiative.

Section on Zoning

Zoning (residential, commercial, logistics, etc.) is an element … to consider for establishing a cycle logistics initiative.

Section on City Geography

The city's elevation (topography) is … for establishing a cycle logistics initiative. Weather conditions such as temperature, precipitation, and the presence of ice, etc., are elements … for implementing a cycle logistics initiative.

Section on Infrastructure

The presence of cycling infrastructure is … for establishing a cycle logistics initiative.
The presence of shared bike services (e.g., Bixi in Montreal, àVélo in Quebec City) is … for implementing a cycle logistics initiative.
The presence of car-sharing services (e.g., Communauto) is … for implementing a cycle logistics initiative.

Section on Transport Data

The availability of transport data on goods (volumes, origin and destination, etc.) is … for establishing a cycle logistics initiative.

Section on Knowledge and Support in Cycle Logistics

Knowledge and/or expertise in urban logistics and/or cycle logistics are … for establishing a cycle logistics initiative.
Support from professionals with expertise is … for establishing a cycle logistics initiative.

Section on Access to Financing

Awareness of various sources of financing (banks, public financing, ministry grants, etc.) for cycle logistics initiatives is … for establishing a cycle logistics initiative.
Accessibility of knowledge regarding various sources of financing is … for establishing a cycle logistics initiative.

Open Section

In this section, you may use the text boxes to add any comments you find relevant for the implementation of a cycle logistics initiative. All responses will be considered. Thank you for your assistance!

Table A.1 Land use proportions for the selected cities

CUBF_X	count	mean	std	min	25%	50%	75%	max
1	46.0	47,65%	14,18%	26,83%	37,27%	46,11%	55,55%	85,23%
2	46.0	0,12%	0,08%	0,01%	0,07%	0,11%	0,16%	0,37%
3	46.0	0,35%	0,25%	0,06%	0,18%	0,29%	0,45%	1,13%
4	46.0	7,11%	4,62%	0,33%	2,54%	8,19%	11,85%	14,55%
5	46.0	3,78%	1,26%	0,45%	3,10%	3,77%	4,20%	7,26%
6	46.0	4,68%	1,38%	1,88%	3,99%	4,86%	5,63%	7,87%
7	46.0	2,03%	0,78%	0,66%	1,59%	1,96%	2,37%	4,60%
8	46.0	4,32%	4,00%	0,10%	1,75%	3,69%	4,78%	17,31%
9	46.0	30,21%	13,38%	7,65%	20,28%	29,26%	40,04%	56,69%

Table A.2 Ranking results by city

	Non-weighted ranking		Weighted ranking		
Rank	City	Final score	City	Final score	Rank variation
1	Longueil	164	Longueil	137.3	0
2	Laval	171	Laval	140.4	0
3	Saint-Jean-sur-Richelieu	201	Saint-Jean-sur-Richelieu	157.55	0
4	Salaberry-de-Valleyfield	219	Salaberry-de-Valleyfield	171.15	0
5	Mirabel	222	Mirabel	184.7	0
6	Terrebonne	235	Chateauguay	188.15	+3
7	Blainville	239	Blainville	188.55	0
8	Saint-Hyacinthe	240	Vaudreuil-Dorion	194.15	+3
9	Chateauguay	241	Terrebonne	194.6	-3
10	Saint-Jérôme	245	Saint-Hyacinthe	196.5	-2
11	Vaudreuil-Dorion	247	Repentigny	197.35	+2
12	Gatineau	251	Gatineau	201.55	0
13	Repentigny	251	Saint-Jérôme	201.9	-3
14	Chambly	253	Chambly	208.15	0

15	Trois-Rivières	264	Trois-Rivières	208.75	0
16	Boisbriand	267	Boisbriand	219.5	0
17	Sherbrooke	268	Sherbrooke	226.3	0
18	Saint-Eustache	279	Saint-Eustache	226.45	0
19	Brossard	284	Drummondville	235.05	+7
20	Lévis	288	Brossard	235.65	-1
21	L'Assomption	293	Beloeil	236.15	+3
22	Sainte-Thérèse	294	La Prairie	238.5	+1
23	La Prairie	298	Sainte-Thérèse	239.85	-1
24	Beloeil	298	Rimouski	240.15	+6
25	Sorel-Tracy	299	Mascouche	242.7	+2
26	Drummondville	300	Sorel-Tracy	242.95	-1
27	Mascouche	301	Lévis	243.15	-7
28	Saguenay	305	Candiac	247.5	+3
29	Boucherville	308	L'Assomption	247.8	-8
30	Rimouski	309	Boucherville	250.95	-1
31	Candiac	309	Granby	252.7	+3
32	Saint-Constant	315	Saguenay	253.3	-4
33	Saint-Bruno-de-Montarville	316	Saint-Constant	268.05	-1
34	Granby	319	Saint-Georges	275.6	+2
35	Victoriaville	342	Saint-Bruno-de-Montarville	278.3	-2
36	Saint-Georges	343	Saint-Lambert	279.9	+2
37	Val d'Or	347	Saint-Lin-Laurentides	286.85	+3
38	Saint-Lambert	351	Victoriaville	291.8	-3
39	Sainte-Julie	358	Sainte-Julie	295.5	0
40	Saint-Lin-Laurentides	359	Magog	297.45	+1
41	Magog	371	Rouyn-Noranda	303.45	+2
42	Alma	372	Val d'Or	304.6	-5
43	Rouyn-Noranda	375	Alma	309.15	-1
44	Thetford-Mines	408	Thetford-Mines	325.85	0
45	Shawinigan	418	Shawinigan	340.55	0
46	Sept-Îles	458	Sept-Îles	377.35	0

ANNEXE B Article 4 : annexes

Cette annexe correspond aux annexes de l'article quatre, présenté au chapitre sept.

Table B.1 Data matching between Montreal and Brussels

Montreal		Brussels	
Category	Code	Category	Code
Residential (1)	CUBF_1	Residential buildings and outbuildings	VI
Manufacturing industry (2-3)	CUBF_3	Industrial land	III
Transport and public service (4)	CUBF_4	Communication routes	IV
Commercial activities (5)	CUBF_5	Commercial and service buildings	XI
Services (6)	CUBF_6	Public care and accommodation building	XII
Cultural and leisure activities (7)	CUBF_7	Recreation and non-built accommodation	II
Production and extraction of resources (8)	CUBF_8	Agriculture, horticulture, forestry and fish farming	I
		Farm buildings	
		Small and medium-sized farms producing and processing various products	VII
			VIII
		Production and processing of building materials	IX
		Heavy production and processing operations	X
Non operated buildings and water (9)	CUBF_9	Miscellaneous non-built assets	V

Table B.2 Land use proportions for Montreal and Brussels

	Montréal					Brussels				
	N	Mean	Std	Min	Max	N	Mean	Std	Min	Max
Residential (CUBF_1)	80	94.30%	3.00%	80.48%	98.87%	27	92.43%	3.26%	84.75%	97.07%
Manufacturing industry (CUBF_3)	80	0.39%	0.30%	0.02%	3.01%	27	0.02%	0.02%	0.00%	0.09%
Transport and public services (CUBF_4)	80	0.44%	0.36%	0.03%	2.88%	27	0.20%	0.14%	0.05%	0.77%
Commercial activities (CUBF_5)	80	2.05%	1.14%	0.12%	6.05%	27	5.94%	3.34%	0.88%	13.94%
Services	80	1.22%	0.52%	0.31%	3.62%	27	0.09%	0.06%	0.02%	0.24%
Cultural and leisure activities	80	0.16%	0.08%	0.03%	0.42%	27	0.10%	0.08%	0.01%	0.32%
Production and extraction of resources	80	0.03%	0.00%	0.03%	0.04%	27	0.68%	0.81%	0.08%	4.09%
Non-operated buildings and bodies of water	80	1.56%	1.89%	0.25%	13.57%	27	0.54%	0.51%	0.18%	2.59%

Table B.3 Correlation table

	trailer_loans_histo	CUBF_1	CUBF_3	CUBF_4	CUBF_5	CUBF_6	CUBF_7	CUBF_8	CUBF_9	distance_subway	distance_bikesha	distance_carshari	distance_bus	distance_cyc	distance_train	nb_trailers_1km	pop_density	median_income	ave_age	hh_size_mean	unemployed_rate	hh_car	trailer_street
trailer_loans_histo	1.00	0.05	0.01	-0.10	0.05	-0.08	-0.18	-0.07	-0.07	-0.10	-0.12	-0.08	-0.01	-0.04	-0.05	0.31	0.03	0.10	-0.05	0.01	-0.10	0.04	-0.11
CUBF_1	0.05	1.00	-0.42	-0.53	-0.65	-0.21	-0.06	-0.20	-0.46	-0.09	-0.11	-0.15	-0.23	-0.33	-0.48	0.06	0.28	0.31	0.30	-0.10	-0.45	0.22	0.10
CUBF_3	0.01	-0.42	1.00	0.80	-0.05	0.53	-0.03	-0.10	0.17	0.14	-0.05	-0.07	-0.19	0.54	-0.22	-0.04	0.01	0.11	0.00	0.14	-0.14	0.35	-0.13
CUBF_4	-0.10	0.53	0.80	1.00	-0.06	0.71	0.24	-0.05	0.30	0.25	-0.21	-0.04	-0.23	0.39	-0.10	0.01	0.16	0.16	-0.10	-0.05	-0.15	0.14	-0.09
CUBF_5	0.05	-0.65	-0.05	-0.06	1.00	-0.34	-0.26	0.22	-0.23	-0.45	0.00	0.09	-0.49	0.19	-0.42	0.00	-0.47	-0.63	-0.38	0.16	0.76	-0.59	-0.02
CUBF_6	-0.08	0.21	0.53	0.71	-0.34	1.00	0.48	-0.46	0.30	0.43	-0.26	-0.16	-0.53	0.13	-0.29	0.26	0.59	0.41	0.14	-0.07	-0.47	0.25	-0.12
CUBF_7	-0.18	-0.06	-0.03	0.24	-0.26	0.48	1.00	-0.01	0.22	0.31	-0.25	-0.11	-0.30	-0.04	-0.31	0.04	0.36	0.16	0.03	-0.36	-0.24	-0.07	0.20

	trailer_loans_hist	CUBF_1	CUBF_3	CUBF_4	CUBF_5	CUBF_6	CUBF_7	CUBF_8	CUBF_9	distance_subway	distance_bikesha	distance_carshari	distance_bus	distance_cyc	distance_train	nb_trailers_1km	pop_density	median_income	ave_age	hh_size_mean	unemployed_rate	hh_car	trailer_street
CUBF_8	-0.07	-0.20	-0.10	-0.05	-0.22	-0.46	-0.01	1.00	-0.04	-0.32	-0.09	-0.12	-0.45	-0.09	-0.29	-0.28	-0.50	-0.16	-0.35	-0.16	-0.39	-0.15	-0.16
CUBF_9	-0.07	-0.46	-0.17	-0.30	-0.23	-0.30	-0.22	-0.04	1.00	-0.35	-0.04	-0.21	-0.13	-0.03	-0.22	-0.12	-0.05	-0.21	-0.09	-0.00	-0.19	-0.31	-0.11
distance_subway_tram	-0.10	-0.09	-0.14	-0.25	-0.45	-0.43	-0.31	-0.32	-0.35	1.00	-0.09	-0.23	-0.32	-0.11	-0.16	-0.02	-0.40	-0.36	-0.19	-0.08	-0.46	-0.29	-0.02
distance_bikesharing	-0.12	-0.11	-0.05	-0.21	-0.00	-0.26	-0.25	-0.09	-0.04	-0.09	1.00	-0.11	-0.26	-0.08	-0.15	-0.31	-0.36	-0.06	-0.07	-0.19	-0.16	-0.20	-0.16
distance_carsharing	-0.08	-0.15	-0.07	-0.04	-0.09	-0.16	-0.11	-0.12	-0.21	-0.23	-0.11	1.00	-0.42	-0.03	-0.02	-0.32	-0.14	-0.09	-0.09	-0.00	-0.18	-0.01	-0.06
distance_bus	-0.01	-0.23	-0.19	-0.23	-0.49	-0.53	-0.30	-0.45	-0.13	-0.32	-0.26	-0.42	1.00	-0.06	-0.32	-0.27	-0.55	-0.40	-0.26	-0.15	-0.59	-0.26	-0.10
distance_cyc	-0.04	-0.33	-0.54	-0.39	-0.19	-0.13	-0.04	-0.09	-0.03	-0.11	-0.08	-0.03	-0.06	1.00	-0.19	-0.13	-0.12	-0.06	-0.08	-0.13	-0.11	-0.16	-0.04
distance_train	-0.05	-0.48	-0.22	-0.10	-0.42	-0.29	-0.31	-0.29	-0.22	-0.16	-0.15	-0.02	-0.32	-0.19	1.00	-0.27	-0.54	-0.37	-0.21	-0.18	-0.41	-0.04	-0.01

	trailer_loans_hist	CUBF_1	CUBF_3	CUBF_4	CUBF_5	CUBF_6	CUBF_7	CUBF_8	CUBF_9	distance_subway	distance_bikesha	distance_carshari	distance_bus	distance_cyc	distance_train	nb_trailers_1km	pop_density	median_income	ave_age	hh_size_mean	unemployed_rate	hh_car	trailer_street
nb_trailers_1km	0.31	0.06	-0.04	0.01	0.00	0.26	0.04	-0.28	-0.12	-0.02	0.31	0.32	-0.27	-0.13	-0.27	1.00	0.43	0.35	0.06	-0.24	-0.39	-0.13	-0.10
pop_density	0.03	0.28	0.01	0.16	-0.47	0.59	0.36	-0.50	0.05	0.40	-0.36	-0.14	-0.55	-0.12	0.54	0.43	1.00	0.57	0.23	-0.22	-0.64	-0.11	-0.10
median_income	0.10	0.31	0.11	0.16	-0.63	0.41	0.16	-0.16	0.21	0.36	-0.06	-0.09	-0.40	-0.06	0.37	0.35	0.57	1.00	0.25	-0.38	-0.79	-0.37	0.00
ave_age	-0.05	0.30	0.00	-0.10	-0.38	0.14	0.03	-0.35	0.09	0.19	0.07	0.09	-0.26	0.08	0.21	0.06	0.23	0.25	1.00	-0.11	-0.42	-0.44	0.02
hh_size_mean	0.01	-0.10	-0.14	-0.05	0.16	-0.07	-0.36	-0.16	0.00	-0.08	0.19	0.00	-0.15	-0.13	-0.18	-0.24	-0.22	-0.38	-0.11	1.00	-0.42	-0.35	-0.04
unemployed_rate	-0.10	-0.45	-0.14	-0.15	0.76	-0.47	-0.24	0.39	-0.19	-0.46	-0.16	-0.18	0.59	-0.11	-0.41	-0.39	-0.64	-0.79	-0.42	-0.42	1.00	-0.46	-0.02
hh_car	0.04	0.22	0.35	0.14	-0.59	0.25	-0.07	-0.15	0.31	0.29	0.20	-0.01	-0.26	-0.16	-0.04	-0.13	-0.11	-0.37	-0.44	-0.35	-0.46	1.00	0.06
trailer_street	-0.11	-0.10	-0.13	-0.09	-0.02	-0.12	-0.20	-0.16	-0.11	-0.02	-0.16	-0.06	-0.10	-0.04	-0.01	-0.10	-0.10	-0.00	-0.02	-0.04	-0.02	-0.06	1.00

Table B.4 Purposes of uses specified by members

	Brussels		Montreal	
	n	%	n	%
Moving	449	40 %	372	13.30 %
Food and groceries	311	28 %	908	32.47 %
Other	171	15 %		
Tools and manual labour (i.e. DIY)	102	17 %	242	8.66 %
Services	-	-	591	21.14 %
Transport of small goods	-	-	559	19.99 %
Leisure activities	-	-	124	4.44 %

Table B.5 Sources for socio-demographic data

		Montreal		Brussels	
Variable	Explanation	Source	Geographical level	Source	Geographical level
Median taxable income (median_income)	Median taxable income (in euros for Brussels. in Canadian dollars for Montreal)	Statistics Canada (2021)	Census tract (~7.500 inhabitants)	Statbel (2022) Revenus fiscaux par secteurs statistiques	Statistical sector (~ 7.000 inhabitants)
Motorisation rate (hh_car)	Number of cars per household	SAAQ	Forward Sortation Area (FSA)	Statbel (2022) Nombre de voitures par ménage	Statistical sector
Household mean age (hh_age)	Mean age of the household	Statistics Canada (2021)	Census tract	IBSA - Monitoring des quartiers (2023) Age moyen de la population	District
Household mean size (hh_size)	Mean size of the household	Statistics Canada (2021)	Census tract	IBSA.Monitoring des quartiers (2023) Taille moyenne des ménages privés	District
Unemployment rate (%) (unemployed_rate)	Number of citizens without a current employment within the active population for each city	Statistics Canada (2021)	Census tract	IBSA.Monitoring des quartiers (2023) Taux de chômage	District
Population density (pop_density)	Number of imhabitants / km2	Statistics Canada (2021)	Census tract	Statbel (2022) Population	Statistical sector