POLYTECHNIQUE MONTRÉAL
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Developing A Comprehensive Multi-Criteria Decision Analysis (MCDA) Tool for Assessing Traffic Danger with A Focus on Children

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Developing A Comprehensive Multi-Criteria Decision Analysis (MCDA) Tool for Assessing Traffic Danger with A Focus on Children

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DEDICATION

To my loving parents, for their endless love,

To my husband, ***Amir****, for his unwavering support and encouragement,*

To my daughter, ***Deniz****, for her boundless joy and constant source of motivation,*

And To all Iranian girls, for their enduring courage and perseverance.

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This PhD marks the beginning of my research career, particularly in the field of children's traffic danger. It also signifies the start of my immigration journey, bringing new opportunities and challenges. I look forward to continuing my work and contributing to making urban environments safer for children.

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RÉSUMÉ

Les transports posent des défis significatifs pour la santé humaine en raison de leurs externalités négatives, en particulier pour les enfants. Le danger lié au trafic, qui englobe les risques associés aux véhicules à l'intérieur et à l'extérieur, est un problème de santé majeur, causant environ 1,19 million de décès par an dans le monde. Malgré les avancées en matière de sécurité des véhicules, les décès de piétons, y compris ceux des enfants, augmentent. L'environnement bâti joue un rôle crucial dans la santé et le bien-être des enfants, influençant leur activité physique, leurs interactions sociales et leur sécurité.

Les évaluations précédentes des dangers liés au trafic se basent principalement sur les données d'accidents et négligent souvent les interactions entre les différents facteurs influençant ces dangers. Ces études peuvent identifier les lieux sensibles en termes de nombre et de type de collisions, mais elles n'évaluent pas de manière exhaustive les dangers liés au trafic en raison des différents facteurs concernés. De plus, les perspectives des enfants et des parents sont fréquemment négligées dans ces évaluations. Les méthodologies existantes ne tiennent pas suffisamment compte des impacts complexes et inégaux des différentes variables sur le danger lié au trafic. Les méthodes d'évaluation courantes, telles que les analyses statistiques passives et les modèles de simulation active, ne parviennent pas à intégrer efficacement les contributions des divers acteurs. Il manque donc des outils complets capables d'évaluer les dangers liés au trafic à un niveau granulaire, rue par rue, en se concentrant particulièrement sur les usagers vulnérables tels que les enfants.

Pour remédier à ces problèmes, cette thèse propose une méthode complète pour évaluer en détail les dangers liés au trafic, avec un accent particulier sur la protection des usagers vulnérables tels que les piétons et les enfants. En utilisant une approche d’analyse multicritère de décision (AMCD), spécifiquement la méthode MACBETH, cette étude intègre diverses sources de données et perspectives des acteurs pour fournir un indice détaillé de danger lié au trafic.

La AMCD offre un cadre structuré pour intégrer diverses sources de données et prendre en compte plusieurs objectifs conflictuels, ce qui la rend particulièrement adaptée à l'évaluation des dangers liés au trafic. La méthode MACBETH, utilisée dans cette étude, facilite une évaluation complète des divers facteurs influençant la sécurité routière en intégrant les perspectives des acteurs et en gérant les relations complexes. Cette approche permet une évaluation détaillée et granulaire des

dangers liés au trafic, fournissant des informations précieuses pour des interventions ciblées. En utilisant cette méthode, le score global de danger du trafic peut être calculé.

La recherche utilise un cadre complet de AMCD structuré en trois phases : structuration, évaluation et validation. La phase de structuration implique la définition du problème de décision et l'identification des variables pertinentes par le biais de discussions de groupe avec des experts, des parents et des enfants. La phase d'évaluation utilise la méthode MACBETH pour La phase d'évaluation utilise la méthode MACBETH pour construire la fonction de valeur et pour échelonner les constantes. La phase finale consiste à valider le modèle en comparant son classement des intersections avec les classements fournis par les participants et en affinant le modèle en fonction des retours.

L'outil développé a été appliqué aux segments de rue et aux intersections de la ville de Montréal, avec une considération particulière pour les enfants en tant que groupe vulnérable. Les résultats mettent en évidence des préoccupations de sécurité critiques et fournissent des informations exploitables pour les urbanistes et les décideurs politiques visant à éliminer tous les décès et les blessures graves. L'outil permet d'extraire les critères clés en fonction de leur influence sur le danger lié au trafic, conduisant à une évaluation plus précise et complète.

Cette recherche fait progresser de manière significative le discours sur la sécurité routière des enfants en introduisant un nouvel outil d'évaluation des dangers liés au trafic qui intègre les perspectives des acteurs et tient compte des relations complexes et non linéaires entre les variables. Deux modèles distincts ont été développés pour les segments de rue et les intersections, reflétant différents critères et leur importance basée sur les contributions des acteurs. Le résultat est un score global de danger du trafic attribué à chaque segment de rue et intersection.

Cet outil aide les décideurs et les urbanistes à identifier les zones nécessitant une intervention urgente, en assurant la priorité des besoins des groupes vulnérables et en favorisant des environnements urbains plus sûrs et plus inclusifs.

ABSTRACT

Transport poses significant challenges to human health due to its negative externalities, particularly for children. Traffic danger, which encompasses risks associated with vehicles both inside and outside, is a major health issue, globally causing approximately 1.19 million deaths per year. Despite advances in vehicle safety, pedestrian fatalities, including those of children, are rising. The built environment plays a crucial role in shaping children's health and well-being, influencing their physical activity, social interactions, and safety.

Previous assessments of traffic danger primarily relied on crash data and often neglected interactions among various factors influencing traffic danger. These studies can identify locations sensitive in terms of the number and type of collisions but do not comprehensively assess traffic danger due to the different factors related to traffic danger. These studies can identify locations sensitive in terms of the number and type of collisions but do not comprehensively assess traffic danger due to various factors. Their biggest failing is that they often ignore areas so dangerous that pedestrians and cyclists avoid them, resulting in no recorded collisions, yet these areas cannot be considered safe. Moreover, these current models focus on collision trends and do not provide a comprehensive consideration of all influences, often excluding the input of vulnerable groups. Children's and parents' perspectives are frequently overlooked in traffic danger assessments.

Existing methodologies do not adequately account for the complex and unequal impacts of different variables on traffic danger. Common assessment methods, such as statistical analyses and observational models, fail to integrate diverse stakeholder inputs effectively. For instance, simulators used with children tend to focus on training them to adjust to traffic danger rather than understanding traffic danger from the children’s perspective, reflecting a rather adult-centric viewpoint. Therefore, there is a lack of comprehensive tools that can assess traffic danger at a granular street-by-street level, particularly focusing on vulnerable road users like children.

To address these issues, this thesis proposes a comprehensive method for assessing traffic danger in detail, with a particular focus on protecting vulnerable road users such as pedestrians and children. By employing a Multi-Criteria Decision Analysis (MCDA) approach, specifically the MACBETH method, this study integrates diverse data sources and stakeholder perspectives to provide a detailed traffic danger index.

MCDA offers a structured framework for integrating diverse data sources and considering multiple conflicting objectives, making it particularly suitable for traffic danger assessment. The MACBETH method, used in this study, facilitates a comprehensive evaluation of various factors influencing traffic safety by incorporating stakeholder perspectives and handling complex relationships. This approach allows for a detailed and granular assessment of traffic danger, providing valuable insights for targeted interventions. Using this method, the global traffic danger score can be calculated.

The research employs a comprehensive MCDA framework structured in three phases: structuring, evaluation, and validation. The structuring phase involves defining the decision problem and identifying relevant variables through focus group discussions with experts, parents, and children. The evaluation phase utilizes the MACBETH method to construct the value function and to scale the constants. The final phase involves validating the model by comparing its ranking of intersections with the rankings provided by participants and refining the model based on feedback.

The developed tool was applied to street segments and intersections within the city of Montreal, with special consideration for children as a vulnerable group. The findings highlight critical safety concerns and provide actionable insights for urban planners and policymakers aiming to eliminate all fatalities and severe injuries. The tool allows for the extraction of key criteria based on their influence on traffic danger, leading to a more accurate and comprehensive assessment.

This research significantly advances the discourse on child road safety by introducing a tool for traffic danger assessment that integrates stakeholder perspectives and accommodates complex, and in some cases nonlinear, relationships among variables. Two distinct models were developed for street segments and intersections, reflecting different criteria and their importance based on stakeholder input. The outcome is a comprehensive traffic danger score assigned to each street segment and intersection. This tool aids policymakers and urban planners in identifying areas requiring urgent intervention, ensuring the prioritization of vulnerable groups' needs and fostering safer, more inclusive urban environments.

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LISTE OF SYMBOLS AND ABBREVIATIONS

AHP: Analytic Hierarchy Process

AT: Active Transport

ELECTRE (Elimination Et Choix Traduisant la REalité - ELimination and Choice Expressing the REality)

MACBETH: Measuring Attractiveness by a Categorical Based Evaluation Technique

MCDA: Multi-Criteria Decision Analysis

NOx: Nitrogen Oxides

PA: Physical Activity

PM10: Particulate Matter with a diameter under 10 micrometers

PM2.5: Particulate Matter with a diameter under 2.5 micrometers

PROMETHEE: Preference Ranking Organization Method for Enrichment of Evaluations

SGD: Sustainable Development Goals

TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution

UN: United Nations

VOC: Volatile Organic Components

VMT: Vehicle Miles Traveled

MACBETH TERMINOLOGY

MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique): A multi-criteria decision analysis method that uses qualitative judgments to evaluate and rank options based on their attractiveness across multiple criteria.

Attractiveness: The desirability or preference of an option within a specific criterion. MACBETH measures the attractiveness to rank options.

Qualitative Judgments: Comparisons between two options or performance levels using a predefined scale, expressed as "no difference," "very weak," "weak," "moderate," "strong," "very strong," or "extreme" differences in attractiveness.

Semantic Categories: The seven levels of difference in attractiveness used in MACBETH, ranging from "no difference" to "extreme difference."

Consistency Verification: MACBETH's process of checking the logical consistency of qualitative judgments. If inconsistencies arise, the software suggests ways to resolve them.

Value Scale: A numerical scale derived from qualitative judgments that quantifies the attractiveness of options for each criterion.

Criteria Weighting: The process of assigning weights to criteria based on their relative importance, using qualitative judgments of overall attractiveness differences.

Options: The potential actions or alternatives being evaluated in a MACBETH model.

Performance Levels: The qualitative or quantitative descriptions of how an option performs with respect to a criterion. These are converted into numerical scores in the evaluation process.

Value Tree: A structured model that visually organizes criteria and options, allowing for a clear understanding of the decision-making framework.

Judgment Matrix: A matrix where qualitative comparisons between performance levels are entered and stored for constructing value scales.

Hierarchical Weighting: A process where criteria are weighted at different levels of a hierarchy using fictitious alternatives, enabling more complex and structured decision models.

Reference levels: A reference point used in hierarchical weighting, representing the upper and lower bounds of performance for a criterion.

Interval Scale: A numerical scale where equal intervals represent consistent differences in attractiveness. In MACBETH, qualitative judgments are transformed into interval scales for precise comparisons.

Cardinal data: Cardinal data refers to data that not only indicates order but also the magnitude of difference between the data points. In contrast to ordinal data, which only shows rank (e.g., 1st, 2nd, 3rd), cardinal data allows for meaningful comparison of the differences between values.

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CHAPTER 1 INTRODUCTION

The built environment plays a crucial role in shaping children's health and well-being (Waygood, Friman, Olsson, & Taniguchi, 2017). Elements such as sidewalks, parks, recreational areas, safe pedestrian crossings, and bike lanes are essential for promoting active lifestyles, social interactions, and outdoor play. A well-designed urban environment encourages physical activity, reduces the risk of chronic diseases, and supports mental health by providing safe and engaging spaces for children to explore and socialize. However, traffic has various direct and indirect negative impacts on children's well-being, and transport-related research highlights many contributing factors (Waygood et al., 2019). Individual transport choices and environmental exposures that result from different built environment patterns indirectly affect public health. The choices we make (such as using a car or walking between destinations) and the exposures we experience (such as noise from traffic) influence our health (Marmot, 2012). Therefore, due to the built environment's important role in traffic exposure and health outcomes, alternative practices offer opportunities for both improved health and reduced exposure.

Transport poses a significant challenge to human health due to its negative externalities on society today. The adverse impacts of transportation on children's health and well-being are particularly concerning. One major health issue related to transportation is traffic danger, which encompasses the risks associated with cars both inside and outside the vehicle. These risks include the potential for collisions, injuries, and fatalities, as well as exposure to hazardous driving conditions and behaviors. Traffic crashes kill about 1.4 million people every year, making them the eighth leading cause of death worldwide (WHO, 2023a). Despite technological advances in safety features and designs that have made cars safer for occupants, pedestrian fatalities are increasing more rapidly than car driver and passenger deaths. According to the National Highway Traffic Safety Administration (NHTSA), pedestrian deaths now account for 18% of all traffic-related deaths In the US (NHTSA, 2024). In addition, exposure to transportation crashes was the most common type of potentially traumatic event (refers to collisions that disrupts psychological well-being and physical health, often leading to reduced quality of life and extended work absenteeism) in 2023, affecting 31% of those surveyed in a study in Canada between 2018 t0 2020 (Pei et al., 2023). We decided to focus on traffic danger because it is a major threat to children's (and others') lives and is a significant limiting factor on independent travel (R. Mitra, 2013). Reducing traffic danger is crucial for ensuring that children can safely engage in independent travel and benefit from the well-being advantages associated with it (Waygood, Friman, Olsson, Taniguchi, et al., 2017).

Children are particularly vulnerable to traffic danger due to their reduced experience, ability, and visibility, as well as their smaller size, which increases their risk for injury severity, head injuries, and fatalities (Cloutier et al., 2021). In Canada, motor vehicle traffic fatalities are the third leading cause of death among children aged 1 to 19 (Schwartz et al., 2022). Additionally, the psychological impact of traffic collisions can lead to long-term mental health issues such as anxiety, depression, and post-traumatic stress disorder, especially if left untreated (Yule et al., 2015). Therefore, improving road safety measures and providing adequate post-crash care are crucial to safeguarding children's health and well-being.

Addressing traffic danger requires a comprehensive approach that includes examining the relationship between behavioral factors, traffic and built environment characteristics, and their impact on pedestrian or cyclist collisions or injuries. Previous literature offers various methods for assessing traffic danger using different data such as collision rates which are often assessed through collision hotspots. For example , Bíl et al. (2019) examined crash hotspots and their relationship with built environment variables. In some cases, researchers have used questionnaire data to assess perception of traffic danger such as (Rothman, Buliung, et al., 2015), where the parents perception of traffic danger is investigated. Another method is observational methods such as conflict analysis which are detailed in different research (Zheng et al., 2021). While these methods are valuable for collision analysis and considering behavioral factors, they do not provide a comprehensive assessment of traffic danger by considering all aspects. Firstly, these methods often overlook the interactions among different factors influencing traffic danger. For example, in some statistical analyses, researchers attempted to assess the importance of traffic speed and its relationship to traffic danger. However, these analyses overlooked the influence of other factors, such as traffic volume and the presence of traffic calming measures, which are also crucial in understanding the relationship between speed and traffic danger. In some cases, they ignore the importance of incorporating the perspectives of various stakeholders in traffic danger assessments. Also, while these analyses can identify collision hotspots, they often overlook streets or intersections that are so dangerous that no one dares to use them, resulting in no recorded collisions. Consequently, the absence of collisions does not necessarily indicate safety; on the contrary, these places can be extremely hazardous. To effectively address traffic danger issues across various living environments, it is essential to move beyond focusing solely on specific crash sites and instead accurately measure and assess the level of traffic danger at a street-by-street level. Using detailed approach enables a comprehensive understanding of the numerous factors contributing to traffic danger in different areas, providing a clearer picture of the risk landscape. Emphasizing the protection of vulnerable road users, such as pedestrians and children, is critical in this assessment.

In the context of traffic danger assessment in urban areas, integrating both social and technical factors is crucial for addressing traffic hazards (Auvinen & Tuominen, 2014). This perspective recognizes that traffic systems are complex socio-technical systems where human behaviors, technological components, and organizational structures interact dynamically (Ebner et al., 2019). By addressing these interrelated components, such approaches aim to create better and more accurate traffic danger analysis. A key aspect of this approach is considering human factors, such as driver behavior, pedestrian interactions, and community input, alongside technological elements like traffic signals, road design, and vehicle safety features. By applying this approach to traffic danger assessment, we can enhance our ability to design safer road systems by considering the broader context in which traffic interactions occur.

Stakeholder engagement is crucial in the assessment of children's traffic danger because it brings diverse perspectives and expertise to the table, fostering more comprehensive and effective solutions (Luyet et al., 2012). Involving stakeholders such as parents, educators, urban planners, policymakers, and community members ensures a more holistic understanding and that the unique needs and vulnerabilities of children are adequately addressed. Engaging parents and children in the assessment process provides invaluable insights into the daily challenges and perceived risks associated with walking or cycling to school, which can be overlooked by professionals. The participation of stakeholders can reveal specific contextual factors that contribute to traffic danger, such as high-speed zones near playgrounds or inadequate crosswalks, which might not be evident through statistical analysis alone. The participation of stakeholders also promotes a sense of ownership and commitment to implementing safety measures, as they are more likely to support and advocate for changes, they have helped to shape (Luyet et al., 2012). Engaging stakeholders ensures that interventions are not only technically sound but also socially acceptable and sustainable, ultimately leading to safer environments for children.

Given these discussions and limitations, Multi-Criteria Decision Analysis (MCDA) approaches provide a structured framework for integrating diverse data sources and conflicting objectives (Abi-Zeid et al., 2023). Such a tool provides a structured framework for integrating diverse data sources and considering multiple conflicting objectives, making them particularly suitable for traffic danger assessment. This involves a wide range of stakeholders, including road users and professionals. These methods can accommodate the complex, nonlinear relationships between various traffic danger variables, such as traffic volume, speed, and crash rates, and how they interact with each other. By incorporating these interactions and stakeholder perspectives, MCDA approaches like MACBETH provide a more comprehensive and accurate assessment of traffic safety risks, enabling better-informed decision-making and more effective interventions.

Based on the above discussion, the main objective of this thesis is to develop a tool to better assess traffic danger with special consideration of children's health as a vulnerable group, using a multi-criteria decision-aiding (MCDA) approach. Specifically, this research aims to: firstly, explore the varied pathways between the built environment and children's health with a particular focus on transport externalities, secondly, examine the specific factors that contribute to traffic danger for children based on the insights of different stakeholder groups, and establish a comprehensive definition of traffic danger; and thirdly, develop an MCDA tool to assess traffic danger on the road network, with special emphasis on protecting vulnerable road users such as children.

It should be noted that the objectives of this thesis align closely with the principles of Child-Friendly Cities and the UN Convention on the Rights of the Child. The UN Convention emphasizes every child's right to live in a safe and supportive environment, which includes safe travel opportunities (Articles 31 and 27) (Tobin, 2019). By focusing on traffic danger assessment, this research aims to prioritize children's health and safety in urban planning and transportation systems. This approach not only aligns with Sustainable Development Goals (SDGs) such as Good Health and Well-Being (SDG 3), Reduced Inequalities (SDG 10), and Sustainable Cities and Communities (SDG 11) but also supports the broader vision of creating inclusive, safe, and accessible urban environments for all children (Waygood, Forthcoming). Furthermore, this research incorporates children's voices in the traffic danger assessment process, recognizing them as citizens of our cities and nations, and the future for which we are building our society. Such engagement aligns with the goals of the Child-Friendly Cities Initiative, which advocates for the direct involvement of children in the planning process to ensure their needs and perspectives are considered (Waygood et al., 2019). In the next section, the background of the problem, previous research, the research objectives, and the research approach will be discussed in detail.

CHAPTER 2 CRITICAL OVERVIEW OF THE LITERATURE AND RESEARCH NEEDS

Before delving into the comprehensive analysis of transport and children’s well-being or traffic danger, it is important to note that this chapter does not provide an exhaustive review of these topics. These subjects are thoroughly covered in the research articles presented in the later chapters of this thesis. The purpose of this section is to critically assess the literature and highlight some of the main issues that this doctoral research project aims to address. Specifically, this section will identify the definition of traffic danger, the overlooked interactions between various factors influencing traffic danger, the exclusion of children's perspectives in traditional traffic assessments, and the need for a more integrated approach to evaluating traffic danger that incorporates diverse stakeholder inputs.

Focusing on traffic danger, one of the crucial issues is defining traffic danger and distinguishing it from collision rates and crash risk. Different literature sometimes uses these terms interchangeably, leading to biased conclusions. Collision rate refers to the frequency of collisions over a specific time period and includes various types of collisions (e.g., severe collisions, fatalities) (Edwards & Leonard, 2022) or collisions involving different users (e.g., pedestrians, cyclists, different age groups, or vulnerable groups) (Cloutier et al., 2021).

Traffic danger, on the other hand, pertains to the threat of danger- the likelihood of harm or injury resulting from traffic-related incidents, such as collisions, injuries, fatalities, or behavioral threats - and considers various factors that can increase or decrease these hazards. Traffic danger refers to the inherent risk present in the roadway environment, influenced by factors such as road design, traffic volume, vehicle speeds, and driver behavior (Widener & Hatzopoulou, 2016). In this definition, collision rate is not an appropriate approach since there can be locations so dangerous that certain groups do not cross or walk in them, resulting in no collisions. However, this does not imply that these streets or intersections are safe; in fact, they are extremely dangerous. Unlike places marked with “caution - danger!” signs that acknowledge their inherent danger, such as private construction or industrial sites, roads are public spaces used by everyone in society. Simply avoiding them is not an appropriate solution, as they are essential for our daily lives.

Crash risk, on the other hand, is the probability of a crash occurring and is influenced by both the collision rate and the exposure of road users to these dangers (Merlin et al., 2020). It is typically measured in probabilistic terms, such as the number of crashes per population size or per amount of travel (e.g., road fatalities per billion vehicle kilometers traveled) (OECD, 2014). This distinction is crucial because analyzing crash data alone can be misleading—high danger areas might show few crashes simply due to low exposure, rather than an absence of risk.

Analysing traffic danger, urban and road design can significantly increase potential risk for children. High traffic volumes, excessive speeds, and the lack of safe crossing points can lead to a higher incidence of traffic collisions involving young pedestrians and cyclists (Rothman, Buliung, et al., 2014). Such dangers not only pose immediate physical risks but also contribute to psychological stress and anxiety about traveling through these areas (Yule et al., 2015). Fear of collision can deter children from engaging in outdoor activities, leading to sedentary lifestyles and associated health problems such as obesity and cardiovascular diseases (Alonso et al., 2017). Ensuring a built environment that prioritizes traffic safety is crucial for protecting children from these dangers and promoting their overall health and well-being.

Traffic danger is also one of the most significant barriers to children's independent travel (R. Mitra, 2013). High traffic volumes, speeding vehicles, and poorly designed streets create a hostile environment that hinders children's ability to travel freely and safely (Buliung et al., 2017). This leads parents and guardians to restrict children's outdoor activities, limiting their opportunities for physical exercise, social interactions, and experiential learning (Ikeda et al., 2018). Such a response can result in a loss of confidence and reduced spatial awareness in children, further diminishing their ability to navigate their neighborhoods independently. The constant threat of traffic collisions not only poses immediate physical risks but also fosters an atmosphere of fear and anxiety that can undermine the overall well-being and development of young pedestrians and cyclists (Jones et al., 2021). Thus, addressing traffic danger is crucial to enhancing children's independent mobility, ensuring they can explore their surroundings with confidence and safety.

Researchers have focused on the built environment's role in shaping traffic danger, highlighting factors such as street design, traffic features, and active transportation infrastructure (R. Ewing & E. Dumbaugh, 2009; R. Mitra, 2013; Rothman, Macarthur, et al., 2014). Furthermore, the perceptions of safety by parents and children in relation to the built environment are critical in understanding and mitigating traffic danger (Amiour, Waygood, & van den Berg, 2022; Cloutier et al., 2021). This holistic view underscores the importance of not only improving the built environment to reduce inherent dangers but also addressing exposure levels to decrease the overall crash risk.

Background of traffic danger assessment

Traffic danger assessment encompasses various methodologies aimed at identifying, analyzing, and mitigating hazards associated with road use (Sheykhfard et al., 2021). Most of these approaches focus on crash analysis or consider the crash rate as the main variable. Each approach offers unique strengths and insights, contributing to a comprehensive understanding of traffic danger. Overall, traffic safety assessment can be classified into three main groups: examining the causes of crashes (traditional assessment), simulation or observational assessment, and stakeholder engagement methods, which will be explained in detail below.

Research on traffic danger that examines the causes of crashes often utilize crash databases or surveying the community (Lakim & Ghani, 2022). One commonly used safety analysis approach is identifying crash-prone sites by analyzing crash databases using statistical models (Bíl et al., 2019; Harirforoush & Bellalite, 2019; Zahran et al., 2021). However, this method's accuracy heavily relies on the quality and completeness of data recorded in crash reports by police officers and experts. Inaccuracies or omissions in these reports, whether unintentional or deliberate, can lead to flawed results in crash prediction models (Chung & Chang, 2015). An example of this approach is hotspot analysis, a widely used method in traffic safety research that focuses on identifying specific locations with a high incidence of traffic crashes. By analyzing historical crash data, this approach highlights areas where interventions are most needed. For instance, Zahran et al. (2021) evaluated traffic crash hotspots using historical crash data on a section of a road, and Harirforoush and Bellalite (2019) identified traffic collision hotspots on a roadway network using network kernel density estimation.

Another approach within this group is using questionnaire data for traffic danger analysis. Questionnaires and surveys are widely used in traffic safety research to gather data on road user attitudes, behaviors, and perceptions related to safety (Buliung et al., 2017; Papadimitriou et al., 2013; Rankavat & Tiwari, 2016). This approach involves designing structured questionnaires and administering them to a sample of road users, such as drivers, pedestrians, or cyclists (Lakim & Ghani, 2022). The questionnaire data can provide valuable insights into factors influencing road user decisions, risk-taking behaviors, and safety concerns (Cordellieri et al., 2016). By analyzing the responses, researchers can identify prevalent safety issues, risky behaviors, and potential interventions to improve road user awareness. For example, Using questionnaire, Rankavat and Tiwari (2020) tried to find an interrelationship among pedestrians' risk perception, road crossing preferences and actual crash risk However, the reliability of questionnaire data depends on factors like sample representativeness, response rates, and the validity of self-reported information (Brener et al., 2003).

Another traffic danger analysis approach focusing on behavioral factors is post-crash analysis. This type of research deploys monitoring teams to observe road users at crash-prone sites, gathering comprehensive data on driver and pedestrian behaviors and road conditions (Sheykhfard et al., 2021). Additionally, these studies focus on understanding the causes of risky behavior in different road users and their relationship with the surrounding built environment. For example, a study in Brazil analyzed pedestrian and driver behavior at mid-block locations with different traffic calming measures and concluded that the presence of mechanisms facilitating pedestrian crossings, such as raised crosswalks or traffic signals, significantly reduced the number of aggressive or risky crossings (Torres et al., 2020). Overall, this method allows researchers to better understand the factors contributing to crashes and develop targeted interventions to improve road safety.

While statistical approaches provide comprehensive data collection, allowing researchers to investigate crash causes by considering human, environmental/road, and traffic factors (Zahran et al., 2021), they also face limitations. These include the non-availability of certain crash data (Anastasopoulos & Mannering, 2009), underreporting, long intervals required for data assessment, and biases in self-reported survey data due to social desirability (Kawulich, 2012). Additionally, the high costs and logistical challenges of post-crash field observations can limit their scope and statistical significance. Most of the traditional approaches analyzed collision rate in different situation. Given these limitations, researchers have increasingly adopted observational approaches to study crashes and near-miss events, aiming to provide more precise and actionable insights for enhancing road safety.

One effective approach to traffic danger assessment involves recognizing the behavioral differences among road users, including drivers and pedestrians. This can be done using methods like driving simulators and videography analysis.

A common technique for evaluating pedestrian and driver behaviors is installing cameras at crash-prone sites or locations where vehicle-pedestrian collisions are likely to occur. It is possible to collect detailed traffic microdata, such as completed maneuvers, flow direction, and the kinematics of road users at various moments, through videography analysis. Fixed videography allows for the examination of several variables, including time to collision (Kathuria & Vedagiri, 2020), pedestrian characteristics (Zhang et al., 2019), driver behavior (Wu et al., 2018), and traffic flow conditions (Serag, 2014). Another type of videography studies use in-motion cameras try to analyze the behavior and performance of drivers and other road users as they interact with one another. Some variables such as Vehicle speed and stopping distance to the pedestrian (Sun et al., 2015), Drivers and pedestrians' behavior (Sheykhfard & Haghighi, 2018), and driver reaction times to pedestrian crossings (Jurecki & Stańczyk, 2018) have been examined.

Driving simulator studies are another way for understanding road user behavior (Mollu et al., 2018). While on-road tests are limited due to their high cost and hardware requirements, simulation has been widely used to study behavioral factors in traffic danger. These studies examine attitudes and behaviors in various traffic situations, providing insights into decision-making without physical risk (Sheykhfard et al., 2021). They also assess issues like distraction and hazard perception by creating specific scenarios, allowing researchers to observe reactions and determine risks using models such as pedestrian gap acceptance and driver yielding behavior (Yoshizawa & Iwasaki, 2017). Some of the variables analyzed using driving simulators in previous studies include the driver's response process (Dozza et al., 2020), collision likelihood (Kutela & Teng, 2021), and driver distraction (Kutela & Teng, 2021).

Although all discussed traffic danger assessment methods offer significant insights, they come with notable limitations. Driving simulators, for instance, struggle with authenticity and validity, as the real world cannot be fully replicated, leading drivers to exhibit less caution in simulations than in real-life scenarios (De Winter et al., 2012). This discrepancy can affect the reliability of the data. Additionally, driving simulators involve high initial costs for setup, running, and maintenance, particularly for complex research-grade simulators. Another issue is simulator sickness, which occurs because users experience visual interactions without corresponding physical sensations, leading to psychological stress and symptoms ranging from mild dizziness to severe nausea (Brooks et al., 2010). Fixed-camera videography also has limitations, such as failing to capture behavior variations of road users at different road sections, inability to evaluate events from the driver's perspective, and lack of access to detailed driver behaviors (Knoefel et al., 2018).

Furthermore, crash databases and survey data often face challenges related to data completeness and accuracy. These methods can struggle with the non-availability of certain crash data, underreporting, long intervals required for data assessment, and biases in self-reported survey data due to social desirability (Sheykhfard et al., 2021). They also do not adequately address the varying impact of different traffic danger measures and variables, such as the nonlinear relationship between different levels of variables and traffic danger (e.g., a speed increase from 40 km/h to 50 km/h significantly increases traffic danger compared to an increase from 20 km/h to 30 km/h). Additionally, ignoring different stakeholders' (users or professionals) views in the assessment process can lead to incomplete or biased results, as it fails to capture the full range of experiences and insights related to traffic safety.

Overall, these assessment methods primarily focus on limited aspects of traffic danger, such as behavioral factors or crash analysis. They lack a detailed analysis of traffic danger that considers all influencing factors, including built environment factors, traffic characteristics and behavioral factors. Observational research excels at examining near misses as a measure of conflict in many cases, objectively measuring important traffic characteristics such as speed, which are related to design and other contextual factors, and providing an objective view of space usage. However, our aim is to utilize the outcomes of these studies to propose the likely danger levels of streets. Streets at various levels of danger could be further identified, and these tools could be employed to assess whether the estimated danger aligns with objective measures, with adjustments made as necessary. Moreover, the input from different stakeholders has often been ignored, and their perspectives have not been considered as key inputs in the assessment process. These challenges highlight the need for another assessment approach that incorporate stakeholder engagement and correctly aggregate the different variables based on a sound methodological basis. One such approach is multi-criteria decision aiding (MCDA).

MCDA is a family of methods that help individuals and groups explore decisions that matter by explicitly taking into account multiple criteria (Banville et al., 1998). In traffic danger assessment, MCDA approaches provide a structured framework for integrating diverse data sources and conflicting objectives, making them valuable tools for prioritizing road safety interventions and resource allocation decisions in transportation planning and management (Torretta et al., 2017). Several studies have explored the use of MCDA methods like the Analytic Hierarchy Process (AHP) (Mohammad Azlan & Naharudin, 2020), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Kanj & Abi-Char, 2019), and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) for evaluating traffic safety risks and identifying hazardous road segments or intersections (Trivedi et al., 2023).

The AHP, developed by Saaty (1980), is the most common MCDA method used in transport sector decision problems. AHP's basic characteristic is the use of pairwise comparisons to compare options with respect to various criteria and to estimate criteria weights (Mohammad Azlan & Naharudin, 2020). However, AHP suffers from a major limitation: its inability to effectively model and solve complex real-world problems with interdependencies between criteria and alternatives. AHP normalizes values to unity, assuming linear relationships between criteria, which may not accurately reflect real-world complexities (Munier et al., 2021). For example, a small increase in vehicle speed can have a non-linear impact on traffic danger. Further, AHP can only assess a limited number of alternatives which may have problem in urban scale traffic danger analysis with high number of street segments or intersections. Overall, AHP's limitations in handling complexity, dynamic changes, and interdependencies make it less effective for comprehensive traffic danger analysis.

TOPSIS, another MCDA technique used in traffic danger assessment, helps in ranking and selecting from a set of alternatives based on their distance from an ideal solution (Sarraf & McGuire, 2020). For instance, Mirmohammadi et al. (2013) used TOPSIS to prioritize factors affecting collision rates and severity reduction in Iran. Another study assessed the impact of vehicle technical condition on road safety using fuzzy TOPSIS. Although TOPSIS is useful for ranking different variables, it has limitations for traffic danger assessment. The main problem with TOPSIS is that it requires working only with cardinal criteria, which means that the data must be expressed in numerical form and measured on a continuous scale (Çelikbilek & Tüysüz, 2020). TOPSIS calculates the distance to the ideal and anti-ideal solutions linearly, does not provide any formal guidelines regarding the weighting of criteria and as a result the interpretation of the results in unclear (Dhurkari, 2022).

Given these limitations, there is a need for a method that considers the interaction among traffic danger variables and in some cases their nonlinear relationship with traffic danger. MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) is a less common MCDA method in transportation planning, but it offers a novel approach to traffic danger assessment. MACBETH allows for the creation of interval-level scales for criteria, whether qualitative or quantitative, to derive criteria weights and obtain an aggregated score for each alternative (Bana e Costa & Beinat, 2005). This method helps participants reach a consensus by minimizing conflicts during workshops and can rank a large set of alternatives using the user-friendly M-MACBETH software (Donais et al., 2019b). MACBETH has been used in various applications to assess project sustainability, but its application to traffic danger assessment is novel. I chose MACBETH to obtain an aggregated score for each intersection and street segment, allowing for detailed traffic danger assessment of high number of segments and intersections at the urban level.

Stakeholder engagement

Children and parents' perceptions of traffic danger play a vital role in traffic danger assessment (Fusco et al., 2012). Including these perspectives is crucial because they offer unique insights that can significantly enhance the understanding of traffic safety issues. Children, as direct road users, often encounter hazards that adults might overlook, such as dangerous intersections, inadequate pedestrian crossings, or high-speed traffic areas near schools and playgrounds (Christie et al., 2007). Their firsthand experiences and observations can help identify specific risk areas that need targeted interventions. Parents' perceptions are equally important as they influence their children's transportation choices and safety behaviors (Lam, 2001). Parents' views on traffic danger and neighborhood conditions shape their decisions on whether to allow their children to walk or cycle to school, play outdoors, or engage in other forms of independent mobility (Mitra et al., 2014). Understanding these perceptions can help identify broader community concerns and areas where safety improvements are needed.

Despite their importance, children's and parents' perspectives are often neglected in the traffic danger assessment process. This neglect can be attributed to several factors. Firstly, traditional traffic safety assessments have primarily focused on quantitative data such as traffic volumes, speed, and crash statistics, often overlooking qualitative insights from road users. Secondly, there can be challenges in gathering and analyzing input from children and parents, including additional work for acquiring access to them and gaining consent along with the need for appropriate methodologies and tools to capture their views accurately (Smeds et al., 2023). Lastly, there may be an underlying assumption that adults' perspectives and expert analyses are sufficient to address traffic safety issues, leading to a dismissal of the unique and valuable insights that children and parents can provide. Including children and parents in traffic danger assessment offers several benefits. First, it ensures that safety interventions are designed to address the actual experiences and needs of those most vulnerable, leading to more effective and practical solutions. Second, it helps build community trust and engagement, as parents are more likely to support and adhere to safety measures when their concerns are acknowledged and addressed. Third, involving children in the assessment process educates them about traffic danger, fostering safer behaviors and a sense of responsibility from a young age.

CHAPTER 3 OVERALL RESEARCH APPROACH

The aim of this research is to develop a tool to better assess traffic danger with special consideration of children's health as a vulnerable group, using a multi-criteria decision-aiding (MCDA) approach. The built environment can affect children's health and well-being in various ways. Previous studies have mainly focused on specific aspects of children's health in relation to the built environment, such as the relationship between active transport or walkability and the built environment, or how changes in the built environment can promote children's physical activity. However, the comprehensive consideration of all aspects of children's health (physical, social, and mental) in relation to the built environment has been neglected. Different transport externalities can affect children's health in various ways and built environment design can directly influence these externalities. However, the interaction between these negative aspects of transport, the built environment, and children's health simultaneously has been overlooked.

Stakeholder engagement is also crucial in traffic danger assessment as it incorporates diverse perspectives from children, parents, civil servants, and community organizations, helping to identify safety issues not evident in statistical analyses. Engaging stakeholders ensures that the assessment process is informed by real-world experiences, leading to more effective and accepted safety interventions.

Finally, assessing traffic danger is a complex issue that requires consideration of multiple factors, each of which interacts with others and has varying levels of influence on traffic safety. Developing an assessment method that comprehensively incorporates these aspects is a key objective of this thesis.

Contributions of the study

This study makes several key contributions:

1. **Comprehensive Analysis of Built Environment, Transport, and Children's Health: The research offers an overview of the relationship between the built environment, transport, and children's health. It considers the interactions among various**

variables and externalities simultaneously, addressing gaps in previous research that focused narrowly on specific health aspects or isolated factors.

2. **Inclusion of Children and Stakeholders' Perspectives: The study incorporates the opinions of children, parents, and various experts, which have often been overlooked in previous traffic danger assessments. Including these perspectives enhances the accuracy, acceptability, and usability of traffic danger assessments, as it ensures that safety interventions are informed by real-world experiences and concerns.**
3. **Advanced MCDA Approach in Traffic Danger Assessment: By employing the MACBETH method, this research considers the complex nature of traffic danger and the interaction among different variables. This comprehensive approach develops an aggregate index to assess all streets and intersections in the study area with respect to traffic danger. This provides policymakers and urban planners with accurate information to identify areas needing urgent intervention.**

Objective of the Thesis

This chapter presents the overall approach to the research and explain how the articles and following chapters relate to the overall objectives. To address the issues presented in the previous chapters, the overall objectives of this thesis are to:

1. **Explore the varied pathways between the built environment and children's health, with specific consideration of transport externalities.**
2. **Examine the specific factors that contribute to traffic danger for children based on the insights of different stakeholder groups.**
3. **Develop an MCDA tool to assess traffic danger with special consideration of children as a vulnerable group at both street segment and intersection level.**

An overview of how each article relates to the overall objective and each sub-objective is shown in Figure 3.1.

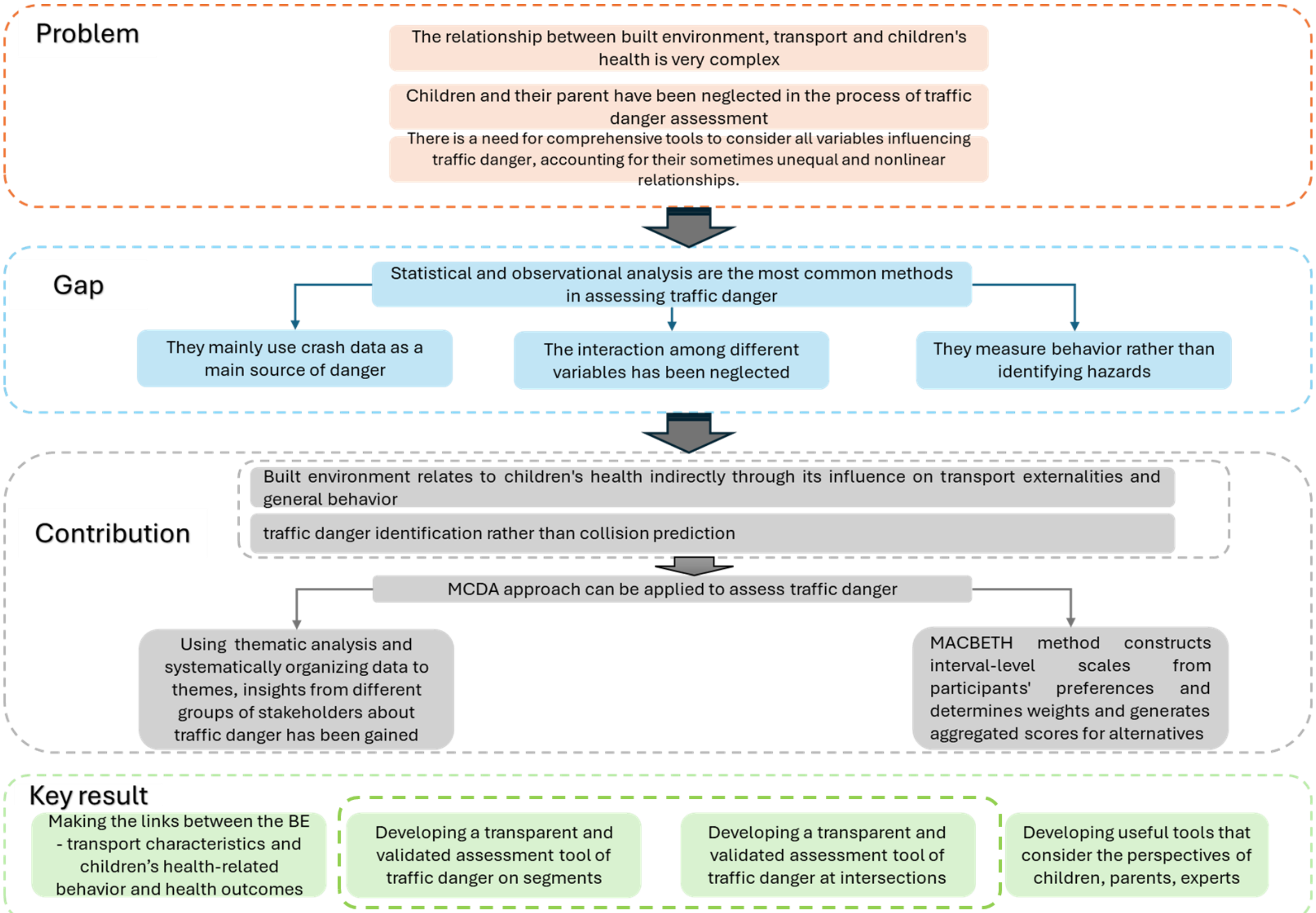

Figure 3.1 The dissertation flowchart

The following chapters include two accepted research articles, one chapter that is ready to submit as a research paper, and one chapter that will be modified to be submitted. Each of those chapters contributes to specific steps towards the overall objectives of this dissertation. Chapter 4 reviews the relationship between the built environment and children's health, with a special focus on transport externalities, particularly traffic danger. Chapter 5 uses thematic analysis and insights from different stakeholders about traffic danger to systematically organize the main themes, which were then used to structure the problem and construct the main criteria in the following chapters. In Chapters 6 and 7, two different MCDA models for assessing traffic danger at street segment and intersection levels are presented. Additionally, the specific and practical implementation of these approaches is discussed. Notably, the first test of assessing traffic danger, emphasizing the multi-criteria nature of traffic danger and its importance in children's accessibility, is detailed in Appendix G.

CHAPTER 4 ARTICLE 1: AN OVERVIEW OF HOW THE BUILT ENVIRONMENT RELATES TO CHILDREN'S HEALTH

In this chapter, the first objective of this dissertation is investigated. That is, a review of relationship between built environment and children's physical, social and mental health with specific consideration of transport externalities. This chapter has been published in "Current Environmental Health Reports" on 28.07. 2023.

This article can be found here: https://doi.org/10.1007/s40572-023-00405-8

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Abstract

Purpose: Explore the varied pathways between the built environment and children's health. The review begins by describing how the built environment and transport infrastructure relate to conditions that lead to health outcomes. The review examines emissions, noise, and traffic dangers in relation to children's physical, mental, and social health.

Recent findings: Evidence is increasing for walkable neighborhoods and health-related behavior such as physical activity. However, diverse land-uses (often supporting walkability) were also found to increase traffic injuries. Cognitive impacts of motorways on children at schools was found. Finally, the relationships between social activities and built environment is beginning.

Summary: The built environment's influence on various physical health outcomes is increasingly clear and is often through a transport pathway. However, the links with mental and social health are less developed, though recent findings show significant results. Having accessible child-relevant destinations is an important consideration for children's health.

Keywords: Built environment, Children's health, Travel behaviour, Exposure, Emissions, Noise, Traffic danger

Introduction

This chapter will give a general overview of how the built environment relates to children’s health. The built environment refers to any man-made change to the natural environment including buildings and transport infrastructure. In our review of the literature, I primarily considered studies that examined people aged under 18 (Assembly & Directorate, 1991; Lansdown & Vaghri, 2022), though the age of majority varies up to 21. The Convention on the Rights of the Child uses 18 (Assembly & Directorate, 1991), though adolescence is defined as up to 19 by the WHO (WHO, 2023b). Finally, for health I will take the World Health Organization’s definition that includes physical, psychological, and social health outcomes (WHO, 2023b).

Several characteristics of the built environment influence children’s health. A major influence on the impacts of the built environment relate to transport as a source of pollution and danger, but also children’s travel options and activity patterns (Frank et al., 2019). It is important to remember that a child's physical environment can affect their health in a number of ways (Christian et al., 2015; Gascon et al., 2016) some environments promote active living (McGrath et al., 2015),while others lead people to have a sedentary lifestyle that can negatively impact their health. The built environment’s influence on children’s health also extends to mental health (Alderton et al., 2019) and evidence is mounting on its relationships with social wellbeing. Therefore, it is crucial to understand the pathways between the built environment, transport, and children’s health and wellbeing (Figure 4.1).

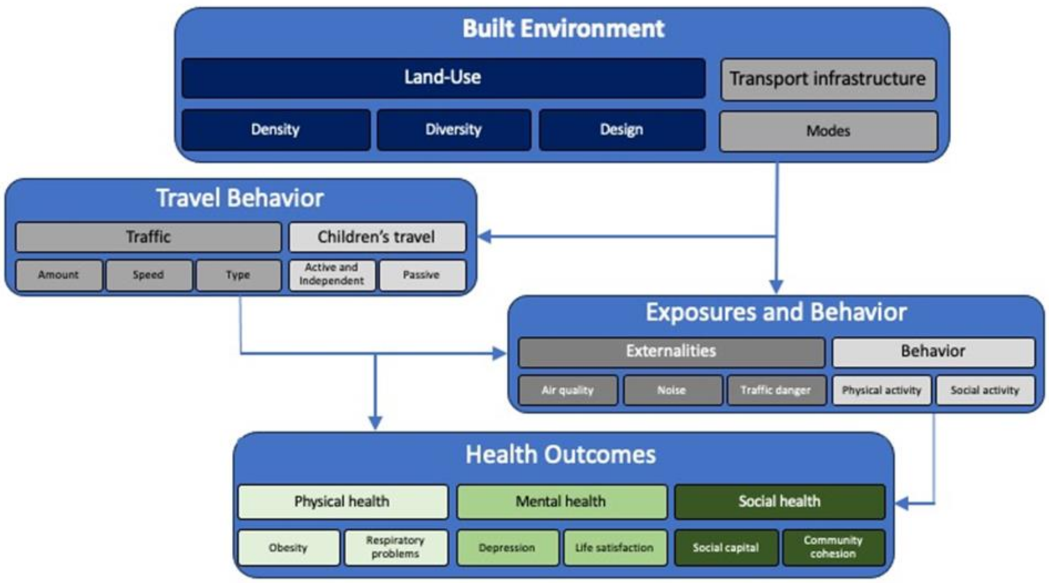

Figure 4.1 General framework of how the built environment affects children's health (Source: Authors' own work).

The built environment can impact children's health indirectly in a number of ways (Figure 4.1 - Built Environment). The two main components are land-use and transport infrastructure. Some authors distinguish pedestrian environments and greenspaces separately (Frank et al., 2019), but I consider those as part of transport infrastructure and land-use respectively. Land-use will determine what activities are possible through diversity which can relate to what children can do, but also whether there are sources of local pollution or environments that reduce pollutants. As density increases it is possible to support a greater diversity of activities, but it also increases development intensity that could limit certain activities including natural spaces. Design can influence not only whether air pollutants and noise are dissipated, but also a number of social determinants of health. Transport infrastructure will play a strong role in what modes are possible which will impact local air pollution, noise, and traffic danger. Greater detail on transport is discussed next.

Transport can influence children's health and wellbeing in many ways (Waygood et al., 2019). The two primary components here are externalities from traffic and how children travel (Figure 4.1 – Travel Behavior). For traffic, the amount (or volume) of traffic can influence the quantity of air borne pollutants. Speed relates strongly to traffic danger, but also traffic noise. The type of traffic is also important as differences exist between public transport (rail and road), private vehicles (size and motor type), and active modes such as walking, cycling, and scooting. As well, how children travel (e.g., the mode used) can impact their health. Active and independent travel are associated with physical activity during travel, but also relate to different psychological and social measures of health. It should be noted however, that children's independence varies by age and culture (e.g., (Shaw et al., 2015)).

The built environment and travel behavior thus create various conditions that relate to health (Figure 4.1 – Exposures and Behavior). The primary conditions that have been examined in the literature that examine the built environment and transport's influence on health can be grouped into externalities and behavior. Externalities include air quality, noise, and traffic danger mentioned above (Calvente et al., 2016; Glazener et al., 2021). Behavior relates to what types of behavior are associated with different built environments and transport systems. These include physical activities and social activities that impact a child's physical, social, and psychological health.

Finally, many health outcomes are associated with those exposures and behavior (Figure 4.1- Health Outcomes) and those outcomes can be grouped as measures of physical, mental, or social health. Too many outcomes exist to list them all here, but examples of physical health include obesity and respiratory problems. Mental health measures examined in the literature include stress and life satisfaction. For social health, examples include social capital and community cohesion (Cicognani, 2014).

This chapter will give a general overview of how the built environment affects children's health. While the built environment and transport play an important role in health, studies have primarily examined the built environments' impacts on adults, but less frequently on children. There is an obvious research gap in this area because built environment measures are linked to children's health via different pathways. Moreover, it is important to note that strategies to promote health along one pathway may have adverse consequences on the other(Frank et al., 2019). In order to develop more effective health promotion strategies and to avoid unintended adverse health consequences, it is necessary to understand how they interact. As an example, travelling by active means can reduce traffic and air pollution at a regional level (Sugiyama et al., 2012), but if adequate walking and cycling infrastructure is lacking, active forms of transportation may increase the risk of injury.

Our focus in this chapter is on the relationship between the built environment's determinants and children's health. As the built environment influences travel behavior, much focus will be on the negative health outcomes of transport externalities – traffic danger, noise pollution, and air pollution – along with the positive health outcomes, such as physical activity, social interaction, and well-being. Then, on the basis of recent studies, I consider a few changes to the built environment that can improve the health of children.

Literature review

Several searches were conducted primarily with Web of Science Core Collection during the month of January 2023. The search protocol included variations of the terms "child" (e.g., child*, adolescent, youth), "built environment" (e.g., "physical environment", "urban environment"), and the primary health dimensions (e.g., "mental health", "physical health", "social health"). The objective of this overview is not a systematic review and as such, some relationships may be missed. The results reported focus on summarizing findings from various reviews and supplementing where new results exist or where gaps in those reviews are evident. The full search logic can be found in the Appendix A.

4.1.1 The built environment and behavior

This section examines how the built environment relates to physical and social behavior (Fig. 1 – Exposures and Behavior). It can affect what options children have in terms of where to go and whether they can get there by themselves. Accessibility to child-relevant destinations is variously linked to physical activity and active travel but is also linked to various measures of health outcomes (Christian et al., 2015). The presence of parks within 250 m, walkability, and intersection density have been linked to lower obesity (Malacarne et al., 2022a), likely through their capacity to facilitate physical activity including active travel. However, the evidence of a direct link between active travel with obesity is unclear (Schoeppe et al., 2013). Access to nature and open space are positively linked to mental health in early childhood [9], and for children aged 6-12 (Liu & Green, 2023), and one other systematic review on children aged 0-18 found positive associations (McCormick, 2017). However, a more in-depth review found that the results were mixed depending on the measure of mental health (Tillmann et al., 2018) and another on adolescents found inconclusive results for causal associations (Fleckney & Bentley, 2021). One review (Tillmann et al., 2018) suggested that it was not only important to consider the type of mental health measure, but also the type of interaction: accessibility, exposure, or engagement. That recommendation makes a distinction between the indirect effect of land-use and the behavior. However, all reviews suggest that on the whole, natural spaces are correlated with some better mental health outcomes such as stress reduction. (Ye et al., 2022) proposed that greenspaces can help promote health by facilitating physical and social activities and also through restorative experiences and stress reduction.

4.1.2 The built environment on physical activity and active travel

The importance of physical activity for the wellbeing and health of humans cannot be overstated (WHO, 2010). A number of previous studies have demonstrated that regular physical activity can reduce the health risks associated with childhood obesity and chronic diseases (Gao et al., 2018). Childhood obesity increases the risk of diabetes, cardiovascular disease and metabolic syndrome as an adult (Mannocci et al., 2020). Furthermore, there has been increased research on physical activity and children's mental health, including depression, self-esteem, and cognitive development. Depression and cognitive functioning appear to be causally related to outdoor physical activity in children (Shen, 2022). A study conducted in the US with over 35,000 children aged 6 – 17 (R. Ewing & R. Cervero, 2010) found that a few built environment measures such as having a recreational center or library were positively associated with a lower mental health index (higher means more problems reported), but the key finding was related more to participation in activities. A similar result was found in Norway with a study of over 23,000 eight-year-olds, where participation in activities (leisure PA, organized activities) were positively associated with positive mood and feelings, but that the built environment measures of nearby parks and playgrounds were negatively associated. However, those same built environment variables were positively associated with the activities. Such results imply that it is not just enough to have the locations nearby (indirect effect of land-use), but to conduct activities (behavior).

The relationships between the built environment and physical activity (Table 4.1) can be explained in part by land use and transportation (Frank et al., 2019). The land use pattern influences one's activity spaces, as well as the quality and availability of transportation options (R. Ewing & R. J. J. o. t. A. p. a. Cervero, 2010). Various reviews have examined how the built environment relates to children’s physical activity (PA) (Gascon et al., 2016; McGrath et al., 2015; Ortegon-Sanchez et al., 2021) (Ding et al., 2011). McGrath et al. (2015) conducted a review of objective of built environment measures with moderate-to-vigorous physical activity and found either trivial or small associations. They also found that most activities were conducted in urban space and streets rather than green spaces. Gascon et al. (2016) found that the links of PA with green spaces was mixed, though leaning to the positive side. No clear relationship with housing density, street connectivity, or walkability was found in that review. However, a more recent review (Ortegon-Sanchez et al., 2021) using a broader approach found ten different relationships between the built environment and total physical activity, including active travel. In that review, positive relationships were found for numerous built environment components: residential density, land-use diversity, walkability, pedestrian infrastructure, access and proximity to facilities, and availability and proximity to green or public open spaces. Traffic danger was found to have a negative influence, while social environment considerations such as personal safety and social support had positive relationships. One new avenue of study is examining how streets can be used again for places of play. A systematic review of Play Streets, where traffic is forbidden for a period of time, found that evidence is limited but suggests an increase in physical activity (Umstattd Meyer et al., 2019). Finally, a review of interventions (Smith, Hosking, Woodward, Witten, MacMillan, Field, Baas, Mackie, et al., 2017), which helps determine causality, found that improving walkability, the quality of parks and playgrounds, and active travel infrastructure were all associated with better PA outcomes.

Street connectivity was a built environment measure that was found to be inconsistently associated with physical activity in a couple of reviews (Gascon et al., 2016; Ortegon-Sanchez et al., 2021). However, in Ortegon-Sanchez et al. (2021) they highlight that objective measures of PA were associated with greater connectivity while self-reported PA was associated with lower connectivity. Higher connectivity was associated with more active travel, but the lower connectivity is often related to controlling traffic through cul-de-sacs or traffic calming. As such, intersection density’s influence may be moderated by levels of traffic volume.

Numerous research studies have examined the relationship between children's transportation behavior, physical activity levels, and physical health (Ding et al., 2011; Larouche, 2018; Waygood, Friman, et al., 2020). Walking, cycling, and scooting are all forms of active travel where children move themselves by using their muscles, though most research has focused on walking and less on cycling. According to studies, children who use active travel (predominantly walking) are more active than those who use other transportation modes (Schoeppe et al., 2013).

For example, previous research has shown that walking or biking to school can increase children's physical activity, even after school and in the evening (Larouche et al., 2020). It appears that active travel does not substitute for other physical activities and is generally in addition to other PA (Panik et al., 2019). Further, active and independent travel has been found to help children develop their physical, psychological and social health, as well as their cognitive skills as they accumulate physical activity, interact with friends, and explore their surroundings (Waygood, Friman, Olsson, & Taniguchi, 2017). Finally, most active travel is walking, though some evidence suggests that those who cycle are more likely to meet health guidelines (Roth et al., 2012) and reduce psychosomatic complaints (Kleszczewska et al., 2020).

Moreover, better transport infrastructure can encourage active transportation by improving convenience and comfort for pedestrians and cyclists. For example, a systematic review of the literature has indicated that environments that are more walkable (e.g., those that facilitate walking by improving destination accessibility, street connectivity, active transportation infrastructure availability) are associated with greater physical activity for children (Prince et al., 2022). When it comes to density, it is positively correlated to active transport since in dense cities, housing is closer to a range of destinations, increasing children's accessibility and active transport rates (Ikeda et al., 2018). In addition, a positive association between safe active transport infrastructure and physical activity was also observed for children (Audrey & Batista-Ferrer, 2015).

Conversely, environments can also discourage physical activity. Based on a review by Frank et al. (2019), sprawling development patterns are often car-oriented because key destinations are difficult to reach on foot. The level of active transportation for children was lower in neighborhoods with fewer recreational open spaces, lower residential density, lower traffic density, and fewer sidewalks (Duncan et al., 2014).

Table 4-1 Summary of relationships between the built environment and physical activity and health outcomes.

BUILT ENVIRONMENT		BEHAVIORS		HEALTH OUTCOMES		
	Articles	Physical	Social	Physical	Mental	Social
Walkability	(R. Ewing & R. Cervero, 2010) * (McGrath et al., 2015)*, (Malacarne et al., 2022a)*, (Ortegon-Sanchez et al., 2021)*, (Umstattd Meyer et al., 2019)*]	Incr. PA				
Safe AT infrastructure	(Christian et al., 2015; R. Ewing & R. Cervero, 2010)*, (Umstattd Meyer et al., 2019)*,	incr. PA				
Connectivity	(R. Ewing & R. Cervero, 2010)*, (Kleszczewska et al., 2020)+, (Prince et al., 2022)	incr. PA				
Green space	(Christian et al., 2015; McCormick, 2017)* (Tillmann et al., 2018)*, (Kleszczewska et al., 2020)+]	incr. PA			Mental health	
Streets	(R. Ewing & R. Cervero, 2010)*	incr. PA				
Child-relevant destinations	(Schoeppe et al., 2013; Waygood et al., 2019) * (Christian et al., 2015)*, , (Kleszczewska et al., 2020)+]			Better	Better	Bette r
Parks close-by	(Malacarne et al., 2022a)*, (McGrath et al., 2015)*]			Obesity		
Dense, mixed environments	(Christian et al., 2015), (R. Ewing & R. Cervero, 2010)*, (Ortegon-Sanchez et al., 2021)*, (Umstattd Meyer et al., 2019)*]	AT		Incr. PA	Some evd.	Some evd.

+ Overview (Detailed summary of research study); * Review (Synthesizes and critically evaluates findings from multiple studies)

4.1.3 The built environment on social activity

Physical activity is more often studied and various reviews exist. The majority of the results in this section on children are not based on reviews and require further research to build support or refute. Social activity is related to social wellbeing measures such as social cohesion and social networks (Cicognani, 2014). Along with being important for wellbeing (Gross-Manos, 2017; Helliwell & Putnam, 2004) and mortality risk (Holt-Lunstad et al., 2010), various social conditions of one’s living environment relate to children’s PA and AT (Ortegon-Sanchez et al., 2021). As such, social activities relate to social wellbeing which influences health outcomes and resilience. Participating in social activities was found to be positively associated with mood and feelings in a study of over 23,000 eight-year-olds in Norway (Nordbø et al., 2020), but the built environment measure of having nearby playgrounds was negatively associated to the mental health measure, but positively with the social activity. As above, this implies that doing the activity (behavior) is essential, though facilitating (indirect land-use) is an important part.

Child development is a consequence of a variety of influences, such as those of immediate family members, neighbors, and larger cultural and societal influences (Shonkoff et al., 2012). Studies have shown that built environment features such as residential density and the presence of playgrounds are positively associated with social and emotional domains of early childhood development (Bell et al., 2020). In addition, a child's ability to socialize is influenced by the physical form of the environment in which they live (Freeman & Tranter, 2012). It may be the case that children who live in the same family structure, but who live in completely different locations (such as rural and inner city areas) will have different social experiences (Freeman & Tranter, 2012). In some studies, having child-relevant destinations, neighborhood safety measures (from traffic and crime) and parental perceptions of safety affect children's social development (Christian et al., 2015). Similarly, parents’ perceptions of neighborhood cleanliness were associated with prosocial behavior (Edwards & Bromfield, 2009). There is also evidence that traffic risk, stranger danger, and car dependency restrict children's autonomy and social skills development (Murphy & Murtagh, 2010) (Gleeson & Sipe, 2006).

The built environment can impact children’s social health in a number of ways (Table 4.2), though many are through its relationship with transport. The built environment relates to what destinations are available within a reasonable walking distance for children. Other research has shown that children are more likely to meet at friends' homes who live nearby (Waygood, Olsson, et al., 2020a), highlighting the importance of proximity. This is important as other research has shown that children meet up with friends most often on foot (Waygood et al., 2021) so destinations that are within walking distance influence the likelihood of social interaction.

As children are generally found to use more active and independent travel in denser, mixed environments, the built environment indirectly influences outcomes such as higher occurrences of incidental social interaction (Waygood & Friman, 2015; Waygood, Friman, Olsson, Taniguchi, et al., 2017), knowing and interacting with neighbors (Waygood et al., 2021), social activities with friends (Pacilli et al., 2013; Waygood, Olsson, et al., 2020b), and a sense of community (Pacilli et al., 2013). Those in turn are related to mental health measures such as decreased loneliness (Pacilli et al., 2013) and wellbeing (Helliwell & Putnam, 2004). In various studies (e.g., (Kamruzzaman et al., 2014; Mikkelsen & Christensen, 2009), children report that active travel is enjoyable and a means of socializing with friends.

Social exclusion has been found to be a better explanatory factor for children's subjective well-being than measures of material well-being (Gross-Manos, 2017). However, the relationship between social exclusion and the built environment for children does not appear to have been studied. The measure of social exclusion used contains factors which relate to the built environment through accessibility and activity participation. This is another avenue for future research.

Table 4-2 Summary of relationships between the built environment and social activities and health outcomes.

BUILT ENVIRONMENT		BEHAVIORS	HEALTH OUTCOMES		
	Articles	Social	Physical	Mental	Social
Higher density, mixed	(Gleeson & Sipe, 2006; Pacilli et al., 2013)	Local social interactions			Sense of community
Child-relevant destinations	(Christian et al., 2015)*		Develop-ment	Develop-ment	Development
Control/limit motor vehicles	(Freeman & Tranter, 2012),(Edwards & Bromfield, 2009),(Waygood, Olsson, et al., 2020a)	Local social interactions			Social skills development
Residential density; playgrounds	(Nordbø et al., 2020)	Social activities		Emotional	

4.1.4 The built environment and externalities

Children's health is indirectly affected by the built environment through individual transport choices and environmental exposures resulting from different built environment patterns (Frank et al., 2019). Pathways of how greenspace in particular can affect children's health are described here (Ye et al., 2022). They include mostly positive pathways affecting both mental (e.g., psychological restoration) and physical health (e.g., physical activity, mitigating air pollution and noise). That paper discusses various other potentially positive impacts of greenspace, but the studies are too limited in number.

While the built environment can provide positive health outcomes, particularly for physical activity and active transportation, it can also pose significant health risks. In addition to road crashes, transportation-related air pollution is conservatively estimated to result in nearly 200,000 premature deaths each year, and transportation noise is associated with a burden of disease similar to second-hand smoke (Glazener et al., 2021). Several epidemiological studies have linked air pollution exposure to children's respiratory health (Chen et al., 2019), lung function (Favarato et al., 2014), and childhood cancer risk (Spycher et al., 2015). It has been found that children under five years old living within 100 meters of highways are more at risk of leukemia due to high levels of emissions (Spycher et al., 2015). In addition to its effects on physical health, traffic exposure can also have a negative impact on mental health. Children's mental health can be directly affected by environmental properties such as spatial layout, traffic intensity, noise, and pollution (Pinter-Wollman et al., 2018), with positive correlations found for quality urban environments and green spaces, though questions remain (Fleckney & Bentley, 2021). In urban areas, traffic noise and traffic danger are the most significant factors affecting the mental health of children negatively, but traffic emissions are also a concern (Stansfeld & Clark, 2015). Among children exposed to traffic, sleep disturbance, cognitive development problems, and behavioral problems are some of the most common mental health problems (Basner et al., 2018; Gupta et al., 2018).

Throughout this chapter, I aim mainly to synthesize literature linking the built environment determinants to health via exposure pathways. Most research has focused on air quality, noise, and traffic danger. However, other pathways with the adult population have been identified such as urban heat islands, contamination, climate change, limitations on access to natural environments, and electromagnetic fields (Glazener et al., 2021). To begin, research on natural environments will be summarized as a component of the living environment (i.e., both natural and built environments).

- **Built environment and air quality**

Children are especially susceptible to health problems related to air quality due to various reasons including their developing lungs. A detailed discussion of this topic can be found in (Boothe & Baldauf, 2020). Air quality can relate to traffic, home heating, and cooking. The focus here will be on traffic as a major source of ambient air quality, particularly ultrafine particles (e Oliveira et al., 2019). Pollutants created by traffic can be attributed to three main mechanisms: tailpipe exhaust, abrasion of tires, brakes, and pavement, and resuspension of particles (Waygood et al., 2019). Among the many pollutants emitted by road traffic, particulates with a diameter under 10m (PM10) and 2.5m (PM2.5), ozone (O3), and nitrogen oxides (NOx) are considered to be the key indicators for health effects (Khreis, 2020). Other considerations include carbon monoxide and volatile organic components (VOCs) (Boothe & Baldauf, 2020). Air quality is more commonly associated with respiratory problems such as asthma (Boothe & Baldauf, 2020), but Malacarne et al. (2022b)'s review of the link between the built environment and childhood obesity found strong evidence that traffic-related air pollutants (NO2 and NOx) were related to obesity. Other areas of research have demonstrated links with childhood cancers, autism, and adverse birth outcomes (Boothe & Baldauf, 2020).

The built environment can affect how people travel, which impacts transport emissions (Frank et al., 2019) and the impacts on children's health (Table 4.3). Several studies have directly examined the relationship between the built environment and traffic emissions. These studies have indicated that sprawling development results in more vehicles being used for transportation, leading to higher levels of emissions and air pollution (Ewing & Hamidi, 2015; Khreis, 2020). In addition, mixed-use developments with high densities combined with opportunities to reduce car use like public transit, active transportation, and greenery can help reduce traffic-related pollution (Boothe & Baldauf, 2020). Street connectivity, a measure of transport network design, is negatively related to emissions (Xu et al., 2018) and multimodal streets such as complete streets support the use of alternative modes, such as walking and cycling, and traffic calming reduces car use and emission levels (Liu et al., 2023).

When focusing on children's exposure to traffic emissions, it is important to take into account their lifestyle, particularly the time they spend at different locations. The results of a Dutch study found that children attending schools near motorways were significantly more exposed to soot and PM2.5 than children attending schools in urban settings (Van Roosbroeck et al., 2007). In a review of the impact of ultrafine particles on children's health, (e Oliveira et al., 2019) found that children attending schools with high exposure had substantially smaller growth in all cognitive measures. It has been suggested that active transport such as biking and walking could significantly reduce vehicle miles traveled (VMT) and traffic-related pollution emissions (Park et al., 2017). However, while cycling or walking children may be closer to vehicle emissions and ventilate more, this may cause them to be more exposed to traffic-related pollution (Gao et al., 2022).

Table 4-3 Summary of relationships between the built environment and emissions and health outcomes.

BUILT ENVIRONMENT	EXPOSURE		HEALTH OUTCOMES	
	Articles	Emissions	Physical	Mental
Low density, sprawl, motorways	(Ewing & Hamidi, 2015)*, (Witten & Field, 2020)	Air pollution	Respiratory problems; cancer; obesity	
Motorways near schools	(Spycher et al., 2015),(Park et al., 2017),(Cloutier et al., 2021)	Air pollution		Smaller growth in cognitive measures
Proximity to traffic	(Gao et al., 2022; Park et al., 2017)	Air pollution		

Table 4-3 Summary of relationships between the built environment and emissions and health outcomes (continued).

Presence of green space	**(Mikkelsen & Christensen, 2009)*,(Lee et al., 2008),(Witten & Field, 2020)**	**Air pollution**
Mixed land use	(Wu et al., 2019), (Lam et al., 2021)	Air pollution
AT infrastructure	(Witten & Field, 2020)*	Air pollution

* Review

- **Built environment and traffic danger**

Traffic danger is one critical direct negative effect of transportation on human health (Cloutier et al., 2021). There are risks associated with cars both inside and outside the vehicle with the majority of children in wealthy countries being killed as passengers (L. Rothman et al., 2020). Traffic crashes kill about 1.4 million people every year, making them the eighth leading cause of death worldwide (Organization, 2015a). Since school-aged children are among the most vulnerable groups to traffic injuries, many efforts have been made to enhance traffic safety for them. A summary of the findings is shown in Table 4.4.

There have been a number of studies investigating the impact of the built environment on children's traffic collisions (Cloutier et al., 2021; Rothman et al., 2021). In terms of diverse land use, a positive relationship was found between mixed and diverse land use and injuries among children [80]. Generally, mixed land use includes all types of land usage, including residential, commercial, institutional, and industrial (Cloutier et al., 2021). In one study, mixed and non-residential land use effects on children's traffic safety at intersections and mid-block crossings were examined. At intersections, mixed land use negatively affected children's traffic safety, but at mid-block crossings, it did not appear to have a substantial effect (Bennet et al., 2015). Regarding children's destinations, school location plays an important role in child safety since schools are the center of daily activities for school-aged children (5 to 12 years old). It has been found that schools are high-risk crash locations (Bennet et al., 2015), likely because they are convergence points for children and traffic (including parents driving their children). However, many child-friendly destinations remain unexplored with respect to traffic safety. For instance, the result of one study confirmed that child pedestrians are at greater risk of collision in areas near parks and schools (Ferenchak & Marshall, 2017).

Regarding design characteristics, how streets are designed have important health impacts as they influence traffic speed and volumes (Bennet et al., 2015; Cloutier et al., 2021). In previous research, a variety of aspects related to road infrastructure and design were considered, such as the type of road, the road class, the number of lanes, the street width, walking and cycling infrastructure, etc. In a review of children's traffic collisions, traffic volume was found to be positively correlated with child collision frequency and injury rate (Amiour, Waygood, & van den Berg, 2022). Other results have shown that child pedestrian collisions are more likely on large and straight roads with high traffic volumes (Rothman, Buliung, et al., 2014). Related to controlling speed, several studies (Bennet et al., 2015; Cloutier et al., 2021; Rothman et al., 2021) have found that speed humps reduced the number of pedestrian collisions and pedestrian injuries. Moreover, a study found that children within their neighborhoods and in front of their schools were less likely to be injured when speed bumps were present (Torres et al., 2020). According to a systematic review, sidewalks around schools are associated with fewer collisions with children than roads without sidewalks (Rothman, Buliung, et al., 2014). Another study indicated that there is a greater likelihood of school-aged children being involved in pedestrian collisions on streets with a high proportion of missing sidewalks (Bennet et al., 2015).

Children's traffic safety is highly influenced by population density and multi-dwelling density based on previous research. Rothman, Buliung, et al. (2014) found that high multifamily density decreases the risk of child pedestrian collisions. In addition, children's injuries are negatively correlated with population density in several studies (Bennet et al., 2015). However, high population density may increase walking proportions in areas around elementary schools and such areas were found to be linked to high-risk exposure (Amiour, Waygood, & van den Berg, 2022).

Table 4-4 Summary of relationships between the built environment and traffic danger and health outcomes.

BUILT ENVIRONMENT		EXPOSURE	HEALTH OUTCOMES
	Articles	Traffic danger	Physical
Schools, parks	(L. Rothman et al., 2020)	More collisions	More injuries
Wide roads	(Organization, 2015b; Rothman, Macarthur, et al., 2014)*	Incr. speed	Incr. death
Many lanes	(Rothman, Macarthur, et al., 2014)*	Incr. traffic	Injury rate
Speed bumps	(Rothman, Macarthur, et al., 2014)*	reduce collisions	reduce ped. injury
Sidewalks	(L. Rothman et al., 2020)*	Fewer collisions	
Multi-family dwellings	(L. Rothman et al., 2020)*,(Rothman, Macarthur, et al., 2014)*	Fewer collisions	
Traffic calming	(Linda Rothman et al., 2020)*,(Rothman, Macarthur, et al., 2014)*	Reduce collisions	
Lighting	(Rothman et al., 2021)	Visibility	

* Review

- **Built environment and Noise**

Noise pollution occurs from a variety of sources, such as industrialization, social events, transportation, construction activities, and household activities (Basner et al., 2018). In recent years, noise pollution from road traffic has increasingly been shown to be a threat to urban residents' health (Münzel et al., 2021). The term noise pollution refers to any sound that is unwelcome, unwanted, or too loud to cause or be capable of causing disturbance or irritation (Gupta et al., 2018). According to the WHO's published guideline on the burden of disease caused by environmental noise (Berglund et al., 1999), future epidemiological noise research must focus on vulnerable groups, of which children are one (Basner et al., 2018; Pirrera et al., 2010; Tiesler et al., 2013).

In comparison with air pollution emitted by motor vehicles, the relationship between urban environment and traffic noise (Table 4.5) is likely more complicated. Based on previous studies, traffic, population density, urban form elements, and urban morphology, including open space, building facades, shapes, and positions, can have significant impacts on urban noise levels (Frank et al., 2019; Silva et al., 2014). Urban sprawl, for instance, increases total noise emissions since the number of vehicle KMs driven (VKM) and speed increases; however, noise sources are distributed over a larger area, so they are generally located at greater distance from people (Salomons et al., 2012) until they enter more urbanized spaces. Transportation noise (including from airplanes) has been linked to sleep problems in various studies (Basner et al., 2018), but have also been linked to behavioral and emotional problems (Tiesler et al., 2013).

The amount of noise in urban areas is also strongly influenced by land use (King et al., 2012; Zhou et al., 2017). One study on urban land use and noise found that the level of noise is significantly higher in mixed land use areas as compared to residential neighborhoods [94], likely as a result of a concentration of activities. Furthermore, Zhou et al. (2017) found that different types of residential blocks displayed different traffic noise distributions and generally, detached, semi-detached, and terraced houses experience low levels of noise. Similarly, Lam et al. (2013) found that areas with high density of buildings and roads are more likely to suffer from noise pollution. The density of construction also plays a significant role in determining the level of noise pollution. Based on (Guedes et al., 2011) noise propagation from street and road traffic is attenuated in neighborhoods with more construction density because buildings act as obstructions to its free propagation. In urban settings, green spaces, especially vegetation, such as trees, plantings, and green belts, can also reduce noise effectively (Klingberg et al., 2017). An important issue here is that (as mentioned above), low density suburban development styles are often a major source of traffic noise in urban settings. As such, there is a feedback problem where those who create more noise pollution are not suffering that pollution.

In terms of street design, Lee et al. (2008) concluded that narrow roads, dense road networks and complex intersections decreased traffic volumes, and therefore noise pollution. In a simulation of traffic noise, narrow roads (less than 10 m wide), complex road networks, and a high density of intersections all resulted in a lower volume of passenger cars and motorcycles. In general, as traffic volumes decrease, noise pollution decreases (Tang et al., 2007). As such, built environments that limit traffic volumes or better control it should have lower noise pollution.

Table 4-5 Summary of relationships between the built environment and noise and health outcomes.

BUILT ENVIRONMENT		EXPOSURE	HEALTH OUTCOMES
	Articles	Noise	Mental
Spatial layout, facilitate traffic	(Ewing & Hamidi, 2015)	More noise	Sleep disturbance, cognitive development, behavioral problems
Mixed land-use	(R. Ewing & R. Cervero, 2010)	More noise	
Traffic density	(Tiesler et al., 2013)	More noise	Stress (blood pressure)
Green space	(Mikkelsen & Christensen, 2009)*, (Lee et al., 2008), (S. A. Richmond et al., 2022)	Less noise	
Presence of noise barrier	(S. A. Richmond et al., 2022)		

* Review

Potential built environment interventions and children’s health

A variety of literature exists regarding the use of the built environment to improve children’s health (Choi et al., 2017; Wu et al., 2019), though most literature mainly focuses on adults. In general, the main objective is to reduce exposure and encourage people to use active transportation more often so as to reduce externalities related to transport and benefit from positive influences on health related to such daily activities. Overall, in the short term, reducing traffic-related pollutants and improving physical activity may be most effective by focusing on existing infrastructure and vehicles. In the long term, it is also crucial to consider land use planning to improve children's health by implementing built environment changes.

Among the key conclusions from previous studies in terms of reducing traffic emissions is the following: higher densities, a mix of uses, and walkable neighborhoods contribute to lower vehicle distances and less energy consumption (Choi et al., 2017; Kumar et al., 2021). In addition, various built environment interventions have been proposed to reduce traffic noise, including platform barriers, green barriers, and land use zoning (Lam et al., 2021). Sound barriers around high-speed roads are consistently used in countries such as Japan to limit noise pollution in urban areas. Often, it is not feasible or practical to control noise at its source, such as moving vehicles, so noise barriers are a highly effective solution (Lam et al., 2021).

Regarding children's traffic safety, the majority of safety measures have focused on traffic speed and volume as primary sources of danger (Cloutier et al., 2021; S. A. Richmond et al., 2022; Rothman et al., 2021). Several changes can be made as part of environmental and infrastructure interventions, such as speed management and enforcement, better visibility and lighting, road markings, sidewalk improvements, driver information alerts, traffic signs, and traffic calming systems (S. A. Richmond et al., 2022). Traffic calming measures aim to reduce traffic speed and volume and have consequently been found to reduce child collisions (Rothman et al., 2021).

The second group of built environment changes focuses on improving physical activity, particularly active transportation. Due to the fact that both clean air and active transportation are functions of mobility, they overlap considerably (Glazener & Khreis, 2019). Even though previous studies have not focused enough on children, the built environment changes that can improve their physical health can be classified into three groups: (i) increasing accessibility and connectivity of an area or route; (ii) improving safety from traffic; and (iii) improving walking and cycling experiences (Panter et al., 2019). For example, a study found that in a car-oriented environment or one with poor walking and cycling conditions, new infrastructure for safe active travel can encourage children to walk and cycle (Witten & Field, 2020). One meta-analysis found that increasing the connectivity of child-relevant destinations improved walking and cycling and, where infrastructure was well utilized, walking and cycling increased (Ikeda et al., 2018).

Future directions

First, as mentioned, the age of a child is different depending on what source is used. In general, the human brain does not stop developing until the mid to late 20s (Sawyer et al., 2018). As such, future studies should consider expanding the age of a child. As well, as children's transport was an important influence, future research might consider relationships by age and level of independence. In a number of reviews on how the built environment impacts health (Christian et al., 2015; Frank et al., 2019), transport infrastructure and behavior were highlighted as key components. Combined with the externalities, proper infrastructure is key to supporting children's independent and active travel. However, without access to child-relevant destinations, they are stuck in a "nowhere to go" situation. Accessibility to child-relevant destinations is important (Christian et al., 2015; Smith, Hosking, Woodward, Witten, MacMillan, Field, Baas, & Mackie, 2017), but the quality should be considered as well. As such, urban planning tools that measure quality of parks (Mears et al., 2019) and other important destinations will help improve cities for children. The study of transport and health is growing with reviews of the literature for the general population (Glazener et al., 2021) and children-specifically (Waygood, Friman, Olsson, & Taniguchi, 2017) existing. A previous review on transport and health pathways highlighted increasing evidence on climate change, contamination, and electromagnetic fields for adults (Glazener et al., 2021); though electromagnetic fields has also been linked to cognitive and behavioral development problems with boys (Calvente et al., 2016).

Numerous reviews were found for topics such as physical activity, active travel, and traffic danger. However, the relationship between the built environment and children's mental health (though nature/greenspace and mental health is an exception, which was also noted by Ortegon-Sanchez et al. (2021) and social lives appears to be less well studied. For behavior, in this review I covered physical and social activities, but psychological activities are less evident. Conceptual frameworks for both practitioners and researchers were put forward (Buttazzoni et al., 2022) where social and mental measures of health are evident. Further consideration on this is needed. Beyond walking in natural environments for restorative purposes (Hansen et al., 2017), what might such behaviors be? Regarding social health, it should be noted that even though children's social health is related to built environment features, there is not enough evidence available to answer how much different such features can affect children's social health. It may be due to the lack of measures of social health among children. For example, physical health can be assessed based on Body Mass Index (BMI) or respiratory problems, while mental health can be assessed based on stress or depression within the home environment for children. It is important to give more attention to social health measures such as social capital and social cohesion in order to improve our understanding of that relationship.

New research is connecting transport with various health-related conditions and outcomes. However, even though the built environment influences transport behavior, the influence of the built environment is not always examined. A recent study with nine mostly European countries found that active travel was more associated with psychological (e.g., depression, bad moods, problems sleeping) rather than somatic (e.g., headaches, back pain, dizziness) complaints. Although that study found differences between countries, the influence of the built environment was not directly examined. However, the study did mention that part of what might explain more cycling (which was the most associated with lower psychosomatic complaints) was that wealthier European countries had good bicycle infrastructure. As such, one recommendation is that in future studies of transport's impacts on health, the potential influence of the built environment should be examined.

Conclusion

This chapter gave an overview of relationships between the built environment and children's health. The topic is complex and evolving, and not all possible relationships are necessarily mentioned. This overview highlighted how the built environment indirectly affects children's health through its influences on transport and general health behaviors. Direct influences relate to what types of activities are possible at a local level. These can be positive such as spaces for play, restoration, and social interaction, but also negative if it allows for local pollution sources. A major source of local pollution can come from transport, which is influenced by the built environment through what transport infrastructure exists (and thus what it permits), but also the density, diversity, and design of the built environment. The main negative influences that have been studied on children's health have been traffic danger, air quality, and noise. All three are intrinsically linked to transport externalities. Those externalities are associated with a vast array of negative health outcomes, but transport is also positively associated with better health outcomes through children's active and independent travel. Tension however exists between denser, mixed environments that facilitate such travel and a potential concentration of traffic conflicts, air quality, and noise if high-speed and high-volume traffic are prioritized. Fortunately, denser, mixed environments can also better support high-mobility alternatives to personal vehicle travel such as public transport with high service levels. The key message is that a built environment that limits motor-traffic and supports active travel will likely result in better health outcomes for children. Whether there is a threshold effect to this (e.g., too dense) is not clear. As well, it is likely important through the built environment and transport to facilitate access to nature, as various mental health benefits are evident. More research on psychological and social health impacts are especially needed.

CHAPTER 5 ARTICLE 2: UNDERSTANDING THE FACTORS AFFECTING TRAFFIC DANGER FOR CHILDREN: INSIGHTS FROM FOCUS GROUP DISCUSSIONS

In this chapter, I address the second objective of this dissertation: to understand stakeholders' opinions on the definition of traffic danger and to identify the factors that influence it. Utilizing focus group discussions and thematic analysis, I aim to capture and analyze these perspectives comprehensively. The insights gained from this chapter will serve as the foundation for subsequent steps in traffic danger assessment. Additionally, this chapter aims to achieve the objective of stakeholder engagement within the traffic danger assessment process.

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Abstract

Children's safety on urban roads is a critical concern, with young pedestrians and cyclists being among the most vulnerable groups to traffic-related dangers. The prioritization of motor vehicle traffic in road infrastructure poses significant risks to child pedestrians and cyclists navigating city streets. Furthermore, children's independent mobility has been restricted due to traffic danger and their parents' concerns about it. Given the important implications of this issue, a serious gap was identified in that in many traffic danger assessments, attempts have been made to measure traffic danger using proxies such as collision rates. Identifying factors contributing to traffic danger and how they interact and impact traffic are imperative to identify where mitigation is needed to address these problems. This article delves into the complexities of traffic risks for children, focusing on intersections and streets. Six focus groups, including experts (n=3), parents (n=2), and children aged 8 to 12 (n=1), were conducted to gather insights on factors impacting traffic danger. Thematic analysis revealed eight key themes, highlighting the importance of addressing traffic volume, speed, vehicle size, road design, driver behavior, visibility, and land use. These findings contribute to a comprehensive framework for understanding traffic danger for children. Additionally, the article examines how stakeholders' perspectives align with standard measures of traffic danger in the literature.

Keywords

Children, Traffic danger, Focus group, qualitative analysis.

Introduction

Children's traffic safety is of great importance as traffic fatalities continue to be a primary cause of death (WHO, 2023a). Young pedestrians and cyclists are particularly vulnerable to traffic danger, so all factors contributing to the problem need to be examined (Cloutier et al., 2021). It is important to note that generally two types of research have been conducted on traffic danger for children (Amiour, Waygood, & van den Berg, 2022): the first examines the relationship between traffic, context (including road characteristics, land-use, etc.) and child pedestrian and bicycle collisions (objective safety); the second examines the perception of danger by parents and children for active transportation (subjective/perceived danger) which often limits their right to independent travel. However, although associations between various factors and outcomes of traffic danger (e.g., collisions, injuries, death) exist, no measure of traffic danger exists. Traffic danger refers to the inherent risk in roadway environment Influenced by different factors such as road design, traffic volume, speeds, driver behavior. Without a measure of the problem, we must rely on (thankfully) undesirable and infrequent occurrences such as collisions as a proxy. This is akin to measuring weight gain (an outcome), but not having a measure that relates to what causes it (e.g., calories, physical activity). Further, it relies on exposure in that if children are removed from such dangerous locations that a collision cannot happen, it is not the street or intersection is safe, but that it is so dangerous that children's right to travel has been eliminated (similar arguments can be seen in Hillman (1990) work.

Research on traffic danger primarily focuses on adult safety and neglects children's needs and particular characteristics. In previous studies, the primary focus has been on experts' perspectives regarding traffic danger, often neglecting the viewpoints of children and their parents. This article presents the perspective of experts and the perceptions of parents and children on traffic danger in order to identify criteria that should be considered when developing a measure of traffic danger. A qualitative approach is taken to better understand the complexities of traffic danger for children. The insights derived from focus group discussions are used here to unravel the complexities surrounding this issue and to better understand the traffic danger risk that children face on a day-to-day basis. It should be noted that this research is part of a larger project that will develop a multi-criteria-decision-aiding tool for assessing traffic danger in cities that considers children as residents with the right to independent travel.

Literature review

Traffic danger is a significant concern for public health, with 1.2 million of fatalities globally each year with children particularly vulnerable. In Canada, it resulted in 1,768 deaths in 2021 (Transport-Canada, 2021). Among these fatalities, 15.8% were pedestrians, and 6.7% were youths aged 4-19. Besides physical harm, traffic danger also restricts children's independent mobility, impacting their societal participation (R. Mitra, 2013). Understanding the factors that create traffic danger is crucial (Xu et al., 2020).

There are several factors that influence traffic danger within the built environment, infrastructure design and traffic characteristics. These factors include traffic volume, speed, and presence of conflict points resulting from street design (Smith et al., 2020). Recent reviews have shown that the built environment significantly influences children's collision risk (Abdollahi et al., 2023; Amiour, Waygood, & van den Berg, 2022; Cloutier et al., 2021; S. Richmond et al., 2022). Factors such as pedestrian density, road density, crossing major roads, and mixed land use all affect injury frequency. Additionally, the design of intersections, the presence of pedestrian crossings, and the availability of safe footpaths are crucial elements that impact children's traffic safety. For instance, S. Richmond et al. (2022) concluded that road features like traffic calming measures, adequate lighting, and proper signage can significantly mitigate traffic danger for children.

Many studies in the field of child pedestrian safety have overlooked the perspectives of children themselves concerning their own safety. Including children's perspectives in safety research is important, as their unique viewpoints can contribute to a more comprehensive understanding of traffic safety and hazard identification (Meir et al., 2015).

Studies indicate that children's active mobility is shaped by parental views on traffic safety and neighborhood conditions (Mitra et al., 2014). In Australia, focus group discussions with children and parents underscored the importance of family routines, neighborhood characteristics, social norms, and safety in shaping independent mobility experiences (Crawford et al., 2017). Although traffic danger is often given as a reason to restrict children’s independent, the factors driving parental perceptions of traffic danger remain inadequately explored. Research has identified disparities between objective traffic danger measures and the perceptions of parents and children, revealing a gap in understanding (Amiour, Waygood, & van den Berg, 2022).

The complexity of traffic danger assessment is evident in the literature (Bao et al., 2012; Fancello et al., 2019; Yannis et al., 2020). Bao et al. (2012)considered the multi-objective characteristics of traffic danger indicators. Yannis et al. (2020) mentioned the importance of decision makers' opinion in traffic danger. This complexity stems from the intricate interplay of various factors. As we discussed previously, different variables—such as road design, driver behavior, and condition of traffic —affect traffic danger, each with a complex relationship to the overall risk.

However, knowledge on children's and parents' perspectives typically only mentions traffic danger without much nuance. Further, studies on traffic danger focus on the outcomes such as collisions, but not on what creates traffic danger. When examining such an issue it is important to include the individual directly impacted, especially if they are a vulnerable group. To get at the complexity of traffic danger multiple perspectives will be gathered including those of experts, parents, and children. The study sought to gain understanding of participants' views and lived experiences in relation to traffic danger. Children as vulnerable users, parents as adults attuned to the dangers imposed on children, and traffic experts as adults with specialized knowledge.

In order to understand the details of traffic danger for children, a number of perspectives must be explored. These perspectives include different groups of stakeholders: children are a key vulnerable user, parents are the adults most likely attuned to dangers for children, and traffic experts have professional experience and knowledge on the subject. The perspectives of these groups are sought through focus groups as qualitative methods are an appropriate means to investigate individual and group attitudes, beliefs, and perceptions (Stewart & Shamdasani, 2014). Focus groups are a powerful tool for gaining insight into the nuances of traffic danger for children (Agran et al., 2004; Stewart & Shamdasani, 2014). Focus groups are open in nature, allowing unknown opinions to emerge, both from individuals and from groups. In traffic safety studies, focus group discussions have proven to be a valuable tool for gaining insights from these different stakeholders (Adler et al., 2019). The use of focus groups is an effective and convenient way to collect data about the perceptions, attitudes, and beliefs of children, youths, and parents (Adler et al., 2019).

The objectives of this paper are a) to identify the specific factors that contribute to traffic danger for children, as identified by children, their parents, and traffic experts, b) to explore the differences and similarities among these key stakeholder groups, and c) to examine how their understanding of traffic danger aligns with or diverges from the established knowledge base.

Methodology

Structured focus groups were conducted separately with 8 experts of a variety of backgrounds, 14 children between the ages of 8 and 12, and 12 parents. Children aged 8-12 were chosen as this is often the ages in North America when many children begin to do independent trips (A. Cervesato & E. O. D. Waygood, 2019), making their experience with traffic more pertinent as parents likely judge traffic when escorting them when they are younger. When children are younger, parents typically assess and monitor the traffic environment closely—evaluating factors like traffic speed, visibility, and potential hazards—to ensure their children's safety. Focus groups serve as a valuable qualitative method to gather these perspectives, allowing for the emergence of unknown opinions (Adler et al., 2019). They offer a convenient means to collect data on the perceptions, attitudes, and beliefs of children, parents, and experts, providing detailed insights into the phenomenon under study. The qualitative analysis process was divided into four steps, summarized in Figure 5.1.

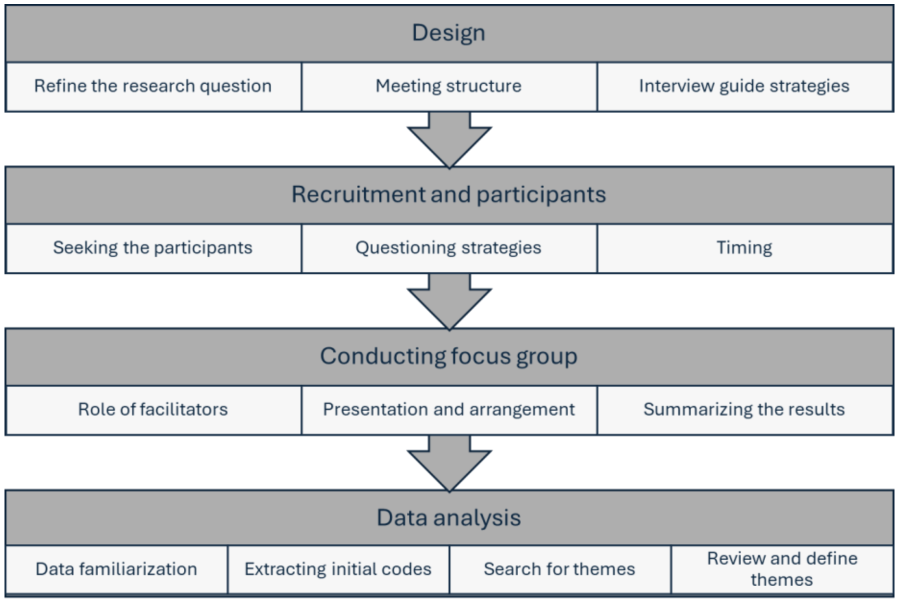

Figure 5.1 Overview of the methodology

5.1.1 Design

Focus groups were conducted across three participant categories: experts, parents, and children. Each was queried about factors impacting children's traffic safety, with follow-up questions designed to delve into the interactions between these factors. Questioning strategies tailored to each group helped elucidate these influences. The experts began with general inquiries following an introductory overview, while parents received a presentation on objectives, transitioning from broad questions to more localized concerns about their neighborhoods. The children's session involved a child-friendly presentation, and concrete questions simplified from pilot testing feedback, progressing from general to specific to better identify traffic danger elements, supported by examples.

Three different questioning strategies and interview guides were developed. The experts' focus groups started with an introduction to the team, the objectives, the method, and a summary of the project. Then, two main questions were asked:

- **"In general, what are the important factors that influence traffic danger for children?"**
- **"Are there other factors that specifically affect children's traffic danger?"**

For the parents' focus groups, I prepared a simple presentation (both in French and English) containing: an introduction of the team, an explanation of the objectives, and a list of questions. The questions for the focus groups with parents and children were tested in pilots with parents and children not involved in the study. Our approach started with more general questions, then more specific questions were asked related to their neighborhood and surrounding area to help them focus on concrete examples. The questions were as follows:

- **What are the key factors that influence traffic danger for children? That question was asked to first gather general ideas of what contributes to creating traffic danger.**
- **What about crossing that street? Are there any factors that can prevent your children from crossing a specific street? This question was asked to focus individuals on traffic danger in the street as children will enter streets whether to cross or fetch an item.**
- **Do you know any dangerous streets in your neighborhood? This was asked to focus parents on a concrete example that they are familiar with to facilitate the next question.**
- **Are there any changes that can be made to make that street safer? This was asked to both help identify issues not previously identified, but also to know what parents thought would make streets safer.**
- **Imagine a safe street WITHOUT sidewalks. Tell us what can make this street safe enough for your child to walk there without an adult? This question was asked to further focus the parents on traffic danger in that public space.**

For children, I prepared a presentation for children and tested it with children. Following the test, adjustments were made to better explain the objectives and elicit diverse responses. The questions were concrete, specific, and easy to understand (according to the children).

- **Are there streets you avoid in your neighborhood? Or streets that you are not allowed to use? Tell us about that street. This approach was used to focus the children on a concrete example they would be familiar with.**
- **Imagine a street that there would be no worries if you walked on it. Tell us about that street. This question was used to elicit responses of what a safe street was from the perspective of the children.**

- **Now, imagine if there is no sidewalk. Tell us about that street. This question was asked to encourage the children to think about the traffic danger on the street.**

It should be noted that ethical approval was granted by the Research ethics committee of Polytechnique Montréal (Application No.CER-2223-63-D).

5.1.2 Recruitment and participants

Various recruitment methods were tailored for each stakeholder group. Experts were invited via online platforms like X and mailing lists of transport professionals. Parents of children aged 7-14 and children aged 8-13 were specifically recruited for their respective focus groups. At the age of 8-13, children start to gain a better understanding of road safety and can realistically estimate risks (Cieśla, 2021). This age range is critical as children begin traveling independently and face unique traffic safety challenges (Schoeppe et al., 2014). I focused on this narrower age group to capture children's direct experiences as pedestrians. Conversely, I included parents of children aged 7-14 to provide insights across a broader developmental range. This allows us to understand the safety concerns and developmental considerations of both younger, more dependent children and older, more independent children. In Montreal, recruitment involved posting flyers in English and French on neighborhood Facebook pages and distributing paper flyers with QR codes for registration in public areas. An incentive of $30 was offered to each participant, both parents and children.

The focus groups were held online using the Zoom application (Zoom, 2024) between May and June 2023. In total, 6 focus groups were held: 3 with experts (n=8 experts primarily in English as they were from various areas of North America), 2 with parents (one in French n=9, one in English n=3), and 1 with children (in French, the dominant language in Montreal n=14). A total of 8 boys and 6 girls were in the children group, with 5 aged 8-9, 7 aged 10-11, and 2 aged 12-13. Parent groups involved three men and nine women across two sessions. As for experts, they came from different fields including engineering, education, planning, public health, and non-governmental organizations (NGO). The duration of the discussions was: 1 hour for children; 1.5 hours for parents; and 3 hours for the experts.

5.1.3 Conducting the focus groups

Focus groups were led by the first author with assistance from a native speaker of French and senior researchers who provided guidance. Participants were informed about recording, and an assistant took notes to mitigate technological issues. An online whiteboard with "sticky-notes" via MIRO (MIRO, 2023) was utilized to foster diverse opinions. Once the participants became accustomed to using sticky-notes, they were prompted to respond in "private mode" to minimize the influence of others' answers initially. After this initial phase, all responses were shared and discussed openly, and any ambiguities were addressed (i.e., why did they think it influenced traffic danger? Is it a positive or negative influence?). Following this, another round was conducted to incorporate missed points, potentially sparked by others' contributions. An illustration of the online whiteboard can be found in Figure 5.2. Different colors are related to different participants.

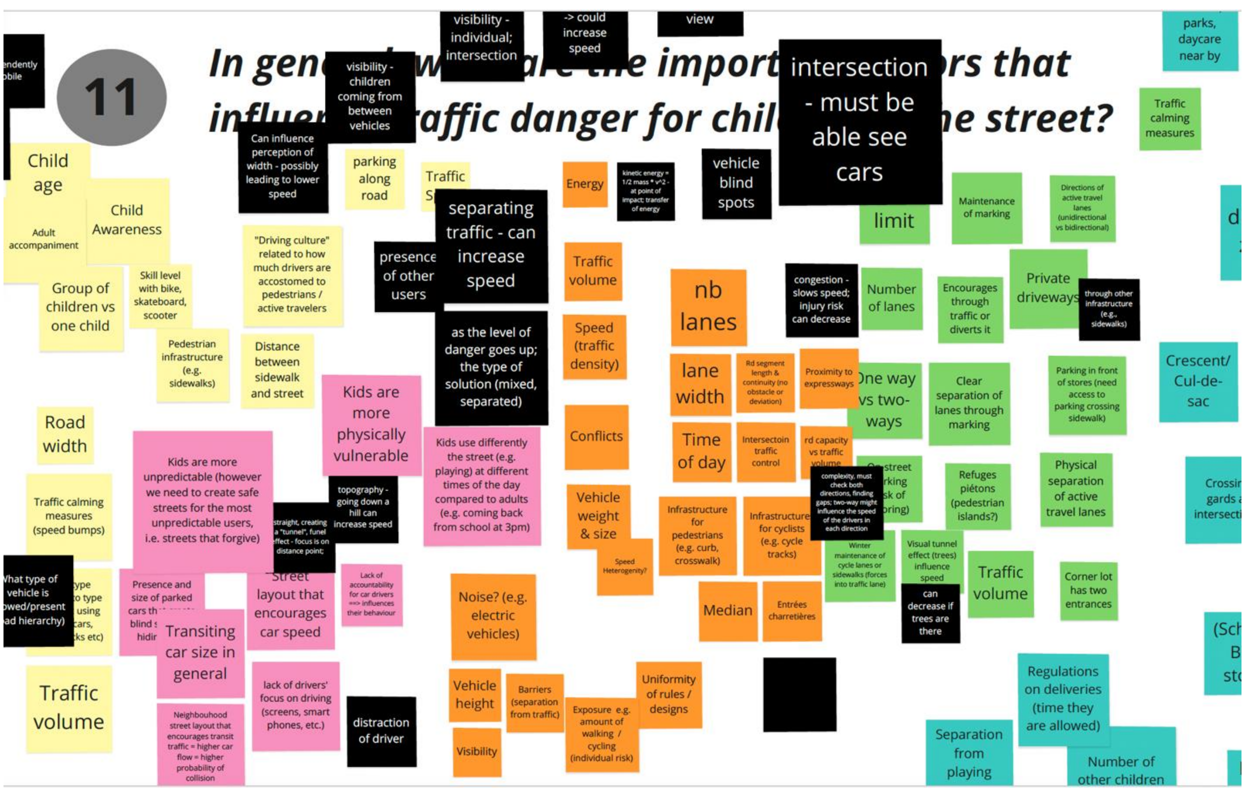

Figure 5.2 Example of Miro screen during an expert meeting

5.1.4 Data Analysis

Considering our emphasis on uncovering themes concerning traffic danger for children, a thematic analysis is one method for analyzing focus group data. A thematic analysis is the process of identifying patterns or themes within qualitative information (Maguire & Delahunt, 2017). Our methodology comprised four steps that are described next.

- **Familiarization with the data**

Initially, audio recordings were transcribed and meticulously reread to ensure that we understood the information completely. As a result of this immersion, participants' perspectives were better understood, paving the way for future analysis.

- **Development of initial codes**

Data were organized into meaningful segments, reducing extensive information into manageable chunks. Participants' inputs and discussions were considered to anticipate potential keywords, as well as which stakeholder groups (parents, children, or experts) mentioned it. This step is illustrated in Figure 5.3. Having a positive sign in front of a keyword means that it increases traffic danger, while having a negative sign means that it decreases traffic danger. The use of these keywords as codes helped the following themes identification.

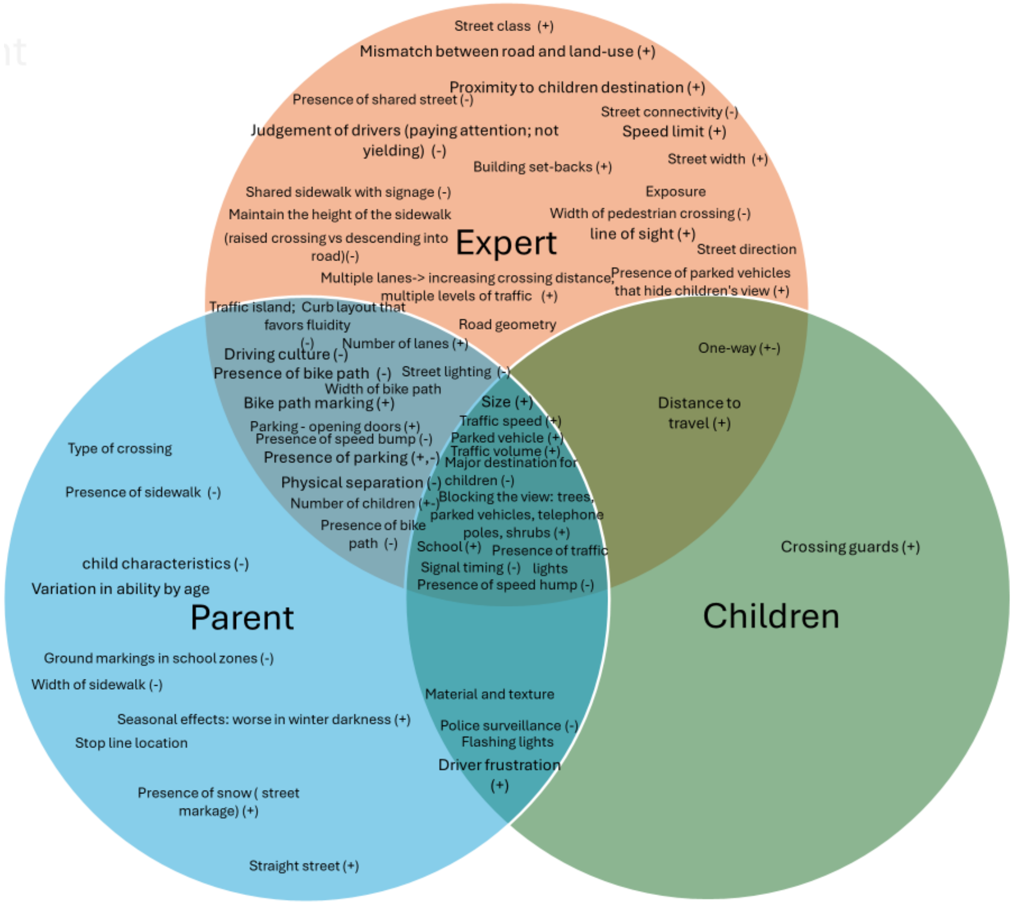

Figure 5.3 Keyword identification by stakeholder type

- **Search for themes**

Eleven main themes emerged from the focus group discussions, with their impacts on traffic danger assessed as positive, negative, or both. Codes were grouped into themes based on similarities; for instance, codes related to traffic volume and vehicle speed were combined into a theme named "traffic characteristics." Figure 5.4 illustrates the classification of these preliminary themes and subthemes.

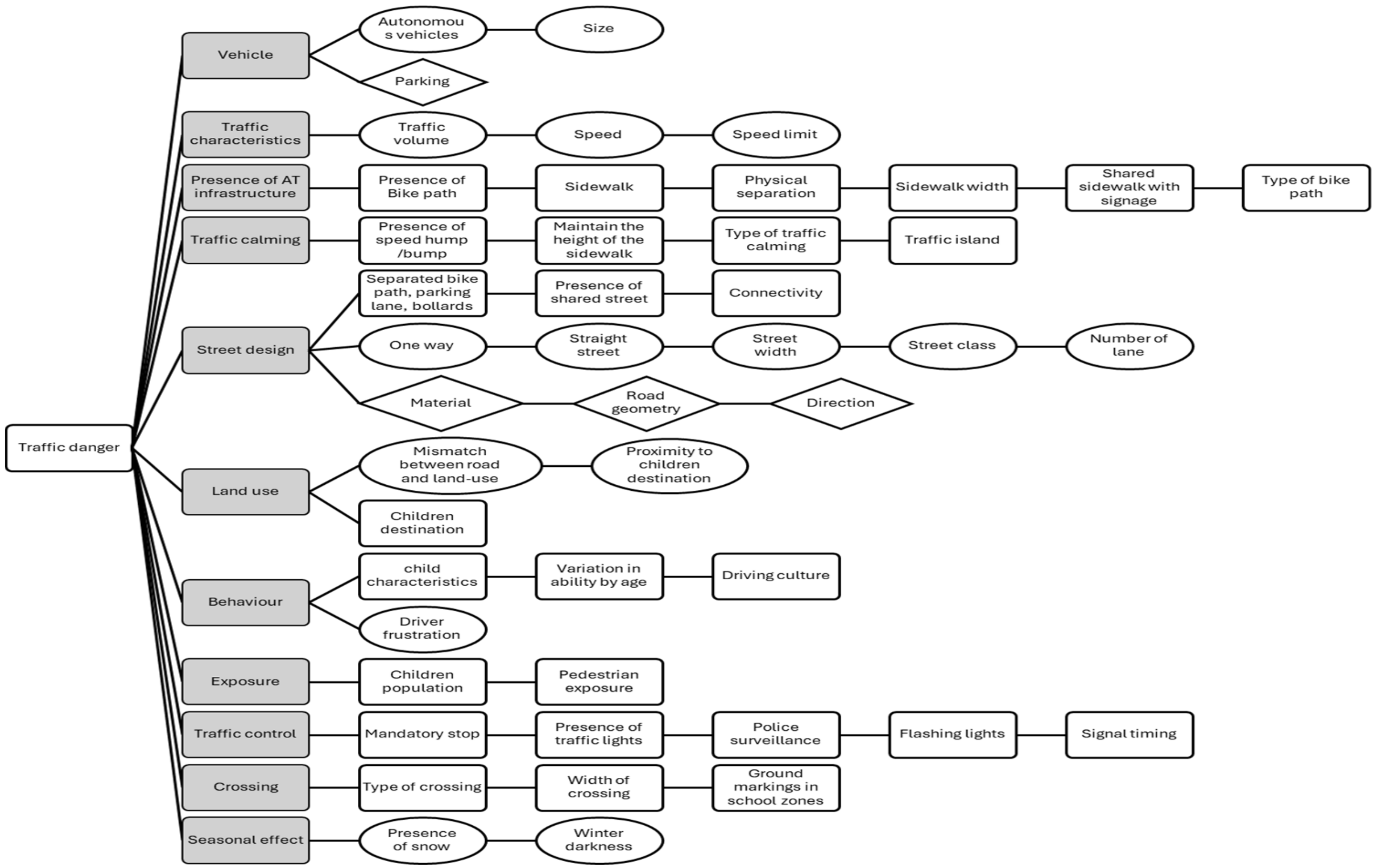

Figure 5.4 Preliminary themes and their effect on traffic danger (positive effect in circle, negative effect in square, both positive and negative effect in lozenge)

- **Review and defining themes**

Step 4 involves a detailed review and refinement of themes identified in Step 3. Each theme's codes are closely examined to ensure they're categorized correctly, with special attention to overlaps. For example, if a code fits multiple themes, its placement is carefully considered. This phase may also uncover new insights, such as design characteristics that impact children's traffic safety, prompting the creation of new themes to address previously unnoticed connections. This step defines the final themes from Step 3 findings, considering the relationships between classes. For example, interconnected factors like speed and traffic volume are combined into a single theme. The objective is to establish a coherent and meaningful thematic structure that captures the complexities of the research topic. Figure 5.5 shows final themes as follows: traffic characteristics, infrastructure/design characteristics, vehicle characteristics, behavioral characteristics, visibility, land use, seasonal effect, and exposure.

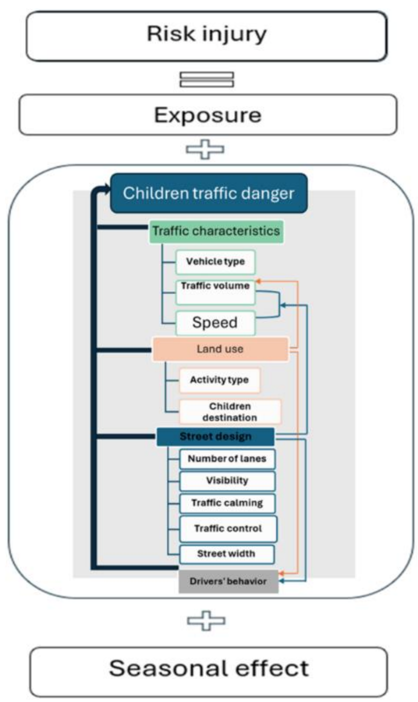

Figure 5.5 Themes and Sub-themes Highlighted During Workshops on traffic Danger for Children

Based on discussions with our participants, particularly the expert group, several key reasons related to exposure have been highlighted. This theme is mainly associated with crash risk, indicating that a higher number of child pedestrians can increase risk injury. Additionally, it's critical to note that traffic danger, exposure, and seasonal effects are all significant factors influencing the risk of injury in children based on the idea of focus group participants.

Exposure directly impacts crash likelihood. A higher number of child pedestrians in an area correlates with an increased risk of injuries. Injuries are significantly affected by traffic danger, which consists of several components. Seasonal effects also play a crucial role in shaping the risk profile for child pedestrians. Seasonal variations impact all aspects of traffic danger and exposure, with changes in weather conditions, daylight hours, and seasonal activities altering the risk profile. Understanding the interplay between these elements—exposure, traffic danger, and seasonal effects—is essential for developing effective strategies to enhance child pedestrian safety.

Results

In this section, I outline themes discussed by each stakeholder group in the focus groups, offering selected responses to illustrate their perspectives. The results of the focus group discussion are summarized in Table 5.1. It should be noted that Consensus variables are those on which all stakeholder groups have the same opinion. Conflicting variables are those on which stakeholders have differing views or are mentioned by only one of the stakeholder groups.

Table 5-1 Summarized results

Theme	**Consensus Variables perceived to influence children traffic danger**	**Conflicting variables (no consensus on their influence on children traffic danger)**
Traffic characteristics	Traffic volume Speed	Importance of traffic volume at intersection Importance of speed in street segment

Table 5-1 Summarized results (continued)

Infrastructure Design Characteristics	**Street width** **Intersection design** **Traffic calming** **Traffic control** **Active transport infrastructure**	
Vehicle characteristics	Presence of trucks	Autonomous vehicle
Behavioral characteristics	Driver’s behavior	Children behavior
Visibility	Position of vehicle	Importance of street design
Land use	Relevance of school zone	Other destinations
Seasonal effect		Daylight hours in the winter
Exposure	Pedestrian volume	

5.1.5 Traffic characteristics

Participants in all focus groups agreed that speed and traffic volume are the most important factors regarding traffic danger for children:

"The biggest effect is traffic speed and volume. Other factors might just be an additional factor, but I wouldn’t consider them as the main factor." (expert, public health specialist)

"To reduce the consequences of the collision, it is necessary to ensure that the speed is reduced." (Father of three children)

"It’s dangerous to cross because people driving on the road drive fast and it's scary."(girl, 10-years-old)

Some experts argued that traffic volume and speed vary based on location: vehicle speed is seen as crucial between intersections (street segments), while traffic volume is what primarily determines traffic danger at intersections.

5.1.6 Infrastructure Design Characteristics

There are many sub-themes in this theme and numerous street and intersection design were discussed, especially in the expert meetings, including street width, number of lanes, street class at intersections, type of traffic control, presence of traffic calming measures and bike path, and one-way streets. Intersections and street segments were dealt with in separate meetings with the experts.

" For a child crossing a two-way street, it might be difficult to assess gaps. At the same time, two-way streets may encourage slower speeds." (Expert, NGO representative)

"Adding a median [also known as a traffic island] on a street is effective because it reduces roadway width. Any measure that reduces road width is effective [to reduce traffic danger]." (Expert, engineer).

Experts also noted the difference between traffic control measures as a crucial factor:

“Fundamentally, a traffic light allows, for half the time, vehicles to go through at speed. This is one of its key purposes. Whereas with a stop sign, all vehicles should come to a stop or near stop. Death is more likely at a traffic light as a result.” (Expert, engineer)

According to parents, characteristics of the intersection are important: street width, type of traffic control, and presence of pedestrian crossings. Parents talked about the difference between pedestrian signals’ protected phase and other situations.

“What is dangerous is when the pedestrian light is at the same time as traffic. We have seen it…. The pedestrian light should have priority........ and cars cannot turn on the pedestrian light. This was not the case before, and it was very dangerous. “(Mother of two children)

Finally, children mentioned a variety of design characteristics, such as street class, traffic control measures, and active transportation infrastructure. They also often compare how different design affects traffic volume and speed:

"When it's small streets and there are stop signs, it feels like it's safe. There are fewer cars that pass quickly. " (Girl, 8-years-old)

"I prefer one-lane streets. Because four-lane streets are often highways, and there, cars go much faster." (Boy, 11—years-old)

5.1.7 Vehicle characteristics

According to all participants, the presence of bigger vehicles and trucks increases the danger level for children on the street and at intersections. All participants, but especially parents and children strongly believe trucks are more dangerous than other vehicles:

"Due to vehicle size increases, SUVs have larger blind spots that can block pedestrian vision. The measures that work today may not work in the future." (Expert, urban planner)

"If the child is still small, perhaps if it's a truck or a vehicle that's higher, he [the driver] won't be able to see the child." (Mother of 8-year-old boy)"

"This is what scares me most: trucks passing by". (Girl, 10-years-old)

“Some cars are very big and can’t see us even if there are lights.” (Girl 8-years-old)

Experts also brought up electric vehicles as part of this theme. According to them, given their quiet operation, children may be less likely to notice their presence, posing a potential safety concern. Additionally, experts expressed concerns primarily about the safety and reliability of autonomous vehicles, highlighting potential issues in their ability to navigate complex traffic situations and respond to unpredictable human behavior.

5.1.8 Behavioral Characteristics

Despite many design characteristics being mentioned by all focus group participants, discussions about traffic danger led to comments about driver and child behavior, particularly at the parents' and children’s focus groups. Parents also felt that children needed to be made aware of traffic danger through education. During the parents’ and children’s focus group, both discussed the importance of drivers observing road safety rules, especially traffic lights, stop signs and speed limits.

"There is a crossing guard next to my school. But it's still dangerous - it's a big street in Montreal and cars that run red lights". (Girl, 11-year-old)

The experts did not mention behavioral factors other than the influence of active transport users on driver’s behavior:

“The presence of other active transport users teaches people that this is to be expected and makes drivers more aware.” (Expert, NGO representative)

5.1.9 Visibility

Another theme mentioned mainly by experts was (a lack of) visibility. For street segments visibility should be lower, narrowing how far a driver can see to naturally lead them to drive slower. However, at intersections, it was argued that children are less visible to drivers because of their height, especially when obstacles are present like trees and parked vehicles in the street.

"Buildings and trees can make pedestrians less visible." (Expert, engineer)

Visibility concerns by parents are mainly explained by the size and positioning of vehicles, as well as how parked vehicles can obscure the visibility of their children to other drivers. They, as well as experts, mentioned the importance of changing infrastructure to improve visibility, especially for smaller children:

"Where the crosswalk was elevated, it allows the child to be higher and to be seen at that time." (Mother of 8-year-old boy)

"You can also design intersections so that crossings are level with sidewalks. This will increase pedestrian visibility." (Expert, urban planner)

5.1.10 Land use

Land use was cited by experts as a factor affecting traffic danger for children. Since school is a primary destination for children, it was much discussed. Several opposing views were expressed about how school presence affects traffic danger for children:

"Land use plays a role. Presence of schools and more commercial areas cause more pedestrian use and a mismatch between land use and road design can be an issue". (Expert, urban planner)

"In the commercial area, the danger is more about the maneuvers of vehicles than the number of pedestrians. " (Expert, engineer)

Parents and children did not explicitly mention the influence of land use, but parents discussed the relevance of school zones:

"The school zones are so small! A child walks more than a school zone to go to school. School zones are like 300 meters before school, it's useless. My daughter walks a kilometer to school. She crosses areas of 50 [km/h]. " (Mother of two children)

5.1.11 Seasonal effect

Another factor mentioned mainly by parents is the seasonal effect. The main issue is related to sidewalk maintenance in winter and changing visibility due to fewer daylight hours in the winter. Furthermore, some participants in the expert group emphasized the importance of renewing street markings quickly after the winter. This factor was not mentioned by children.

"In winter, the biggest concern is how dark it is. You’ve got early nights, late mornings, and children going to school in the dark. That’s a big issue. " (Expert, urban planner)

5.1.12 Exposure

Parents argued that more children walking in the neighborhood might enhance safety, while experts debated exposure, acknowledging its technical complexities with respect to traffic danger:

"The amount of exposure (to cars) and the amount of walking is a factor when you think about the risk of injury. " (Expert, public health specialist)

5.1.13 Interactions

Another key outcome of this research is that the influences of the various factors are not always linear and often interact, meaning that they should not be considered in isolation. For example, “Does more traffic always increase traffic danger?” The experts’ response was “No”, as a lot of traffic moving slowly does not create the same risk of injury or death as less traffic moving quickly. As such, traffic volume and speed should be considered together. Other examples were that speed limits and the number of lanes should be considered together, as more lanes (and wider lanes) can facilitate higher speeds.

Discussion

This study explored the multifaceted factors that influence traffic danger for children through separate focus group discussions involving experts, parents, and children. Stakeholder groups all agreed that traffic volume and speed play a crucial role in contributing to traffic danger for children. This result is supported by previous literature demonstrating the critical importance of addressing these variables to mitigate children's road safety risks (Cloutier et al., 2021). However, despite agreeing on this issue, discussions among experts revealed divergent views on the importance of speed depending on if one is considering intersections or street segments. In previous studies, speed had a great impact on children's traffic danger (Cloutier et al., 2021; Rothman, Buliung, et al., 2014), but occasionally their results differed at intersections. As an example, a study by Bennet and Yiannakoulias (2015) found no relationship between pedestrian-motor vehicle collisions and speed at intersections. Various viewpoints highlight the complexities of the issue, which emphasizes the multifaceted relationship between road design and traffic behavior.

All focus groups recognized the safety hazard posed by larger vehicles such as SUVs and trucks for children. Recent research supports this concern, highlighting the role of vehicle design in traffic danger (Cloutier et al., 2021). These larger vehicles often have substantial blind spots, affecting whether those outside the vehicle are visible to the driver. As children are smaller, this can mean that such vehicles are endangering children more. Other studies connect larger vehicles with children injury severity (Rothman, Buliung, et al., 2014). A holistic approach that integrates considerations for those outside the vehicle into vehicle design is needed to address the danger for pedestrians, particularly children. Implementing greater restrictions, such as speed modulators and sensors for larger vehicles is necessary to mitigate the risk. Previous studies recommend equipping large vehicles with pedestrian/cyclist detection systems, side underrun guards, and blind spot cameras/sensors to improve safety (Shladover, 2021). Intelligent transportation systems that use sensors and cameras to detect pedestrians and automatically apply brakes have also shown promise in reducing collision risks (Oladimeji et al., 2023).

According to our participants, street and intersections design have an influence on children’s traffic danger. Several factors were considered, including street widths, intersection designs, traffic control measures, as well as infrastructure that supports active transportation. While previous studies have found a correlation between road/intersection design characteristics and traffic danger(S. A. Richmond et al., 2022), our study highlights the importance of evaluating this relationship along with traffic characteristics like speed and volume. For instance, to evaluate the impact of street width on safety risks, it is necessary to consider the speed and volume of traffic on that street simultaneously. There may be significant differences in the safety implications of a wider street based on whether vehicles are traveling at high speeds in heavy traffic versus at lower speeds in light traffic. Using this multi-dimensional approach allows a deeper understanding of the risk factors and allows the development of more contextually relevant solutions when compared with viewing design elements in isolation.

Experts highlighted visibility concerns caused by parked vehicles and other obstructions, like buildings, which can obstruct drivers' view of children at intersections. Studies show that barriers to children's visibility at intersections decrease safety (Schofer et al., 1995). However, the experts also noted that limiting driver visibility on road segments could potentially reduce traffic danger by decreasing speeds and focusing the driver's attention closer. While better visibility at intersections may improve safety, wide-open roads can encourage speeding. It is clear that visibility is crucial in design and planning, but its impact on safety varies depending on whether one is assessing a road segment or an intersection.

Both driver and child behavior were emphasized as key factors contributing to traffic danger in the discourse. However, it was clear that children’s behavior related to suffering risk, whereas driver behavior created traffic danger and greater risk. This illustrates the inherent relationship between road users' actions and children's safety. Children highlighted how driver behavior was scary and dangerous when they disobeyed rules, drove quickly, and operated large vehicles. Parents also discussed driver compliance to road rules and speed limits as important, but also talked about teaching children about road safety. On that latter point, a review of educational interventions for pedestrians (14/15 were for children) found no improvement on safety (Duperrex et al., 2002). In fact, research does not show that children's educational interventions reduce actual traffic danger (Akbari et al., 2021). In addition, children's perspectives on drivers who do not adhere to rules highlight the importance of reorienting the conversation towards the danger imposed rather than just the danger suffered. Overall, in consensus with Vision Zero (a traffic safety vision that aims for no deaths or severe injuries), the focus should be on designing safe systems rather than blaming individuals (Kim et al., 2017), especially those who are not creating the danger.

While previous studies have demonstrated the influence of land use types on traffic danger (Abdollahi et al., 2023; R. Ewing & E. Dumbaugh, 2009), our study suggests evaluating the relationship through the lens of pedestrian-vehicle interactions and levels of exposure. Certain land uses like schools or commercial areas can directly increase the number of pedestrians on surrounding streets, heightening their exposure to vehicles and potential conflicts. A more detailed study would be necessary to fully understand how specific land use contexts affect pedestrian behavior, traffic patterns, and the nature of their interactions with vehicles and ultimately affecting risks of injury or death.

Limitations and Future Research

A significant challenge in this research was securing reliable participants for the parents and children's groups, each available for several hours. The initial approach led to undesirable outcomes; in the parents' group, about half showed interest only due to the incentive and were not actively engaged. In the children's group, despite prior instructions for camera activation to verify participants' ages, reluctance to do so caused uncertainties, resulting in the session's cancellation. This problem was absent in the French groups, which included participants previously involved in related research. To address these issues, I suggest avoiding upfront incentives and instead expressing gratitude post-participation to ensure genuine interest in the research. Furthermore, scheduling conflicts prevented the participation of key experts like police officers and policymakers, affecting the study's outcomes.

A strength of this research was the direct involvement of children and parents and the ability to gather information from them about traffic safety. However, only one focus group was carried out with children who were primarily based in Montreal, so it is not known how generalizable the results might be. The context of smaller urban centers or different driving cultures might elicit new or contrasting opinions. Furthermore, the random selection of participants and the mixed gender make-up of the groups may have had an impact on how participants answered focus group questions. Including individuals of different genders in the discussions likely introduced a diverse range of perspectives, experiences, and communication styles, which could have influenced the dynamics of the conversation. The researchers, however, tried to promote a non-threatening, confidential atmosphere that encouraged open dialogue among participants in the focus groups. Our study focuses on understanding the factors that influence traffic danger based on the perspectives of stakeholders. The primary objective is to develop a comprehensive methodology for assessing traffic danger at street-by-street level, enabling cities to identify areas where traffic danger may be limiting children's independence. While we recognize that new technologies, such as interactive applications and simulations, can play a significant role in educating children about traffic danger, our primary results are derived from discussions among participants. These technologies were not within the scope of our focus group discussions. However, other research has explored how to better prepare children to handle traffic danger through such technologies (Trifunović et al., 2024). A future study could specifically examine the impact of these technologies on children's perception and response to traffic danger, potentially incorporating advanced simulations in focus groups to provide deeper insights.

Conclusion

This paper examined the intricate factors influencing traffic danger for children, using insights from experts, parents, and children gathered through focus group discussions. Thematic analysis revealed underlying patterns regarding traffic danger for children. Several themes were consistently discussed by all three stakeholder groups: traffic speed, traffic volume, trucks, and large vehicles, and how road design can increase or mitigate traffic danger. Other potential influencing factors such as land use, education, seasonal effects, and exposure were mentioned but not felt to have the same level of influence.

Each stakeholder group contributed uniquely to the outcomes. Children expressed more concerns about driver behavior and traffic, highlighting larger streets as more dangerous and adults' actions in vehicles as a source of danger. They often relied on emotions to articulate their experiences. Parents provided insights on reduced visibility from inside vehicles, the size limitations of school zones, and the illegal or dangerous behavior of other parents driving their children to school. Experts delved into a broader range of influences, focusing on how street design can exacerbate or mitigate dangerous conditions. They also discussed contextual factors like land use, seen as related more to exposure than increased danger. Another key takeaway from focus group discussion was that many factors had non-linear impacts and interact with other factors so they should not be considered in isolation.

The results support context-specific design interventions, emphasizing how human behavior and road design are interconnected and impact traffic danger and recalling the need for tailored interventions in areas frequented by children, especially outside school zones. This research contributes to the ongoing discourse on child road safety and helps guide future efforts to create safer and more child-friendly urban environments. To ensure child safety in transportation, physical design and human behavior must be integrated. A collaborative approach is essential to ensuring a safe and sustainable road environment, prioritizing children's safety over drivers' efficiency preferences. Due to the multifaceted nature of this problem and the potential interactions between different factors, future research should explore these dynamics and prioritize these key themes. Adopting a multi-criteria evaluation approach could enhance the assessment of traffic danger. In addition, evaluating interventions through discussions with vulnerable users and evidence-based policymaking are crucial.

The findings from this study can be directly applied to enhance urban planning and traffic safety measures. Urban planners and policymakers can use these insights to design safer street environments that prioritize child safety. For instance, implementing traffic calming measures in the areas frequently used by children, improving visibility at intersections by adjusting sightlines to account for children's shorter height, and ensuring safe crossing points near schools can significantly reduce traffic danger for children. Moreover, this research underscores the importance of involving diverse stakeholders, including children and parents, in planning and decision-making processes to ensure that the implemented solutions address the real-world concerns and experiences of the most vulnerable road users.

CHAPTER 6 SAFE STREET FOR THE KIDS: EVALUATING TRAFFIC DANGER IN THE CITY OF MONTREAL THROUGH A MULTI-CRITERIA DECISION-AIDING APPROACH

In this chapter, I investigate the third objective of this dissertation: the development of a tool to assess traffic danger using the Multi-Criteria Decision Analysis (MCDA) approach in street segment level. Building on the insights from stakeholders presented in the previous chapter, I define the problem, evaluate the factors influencing traffic danger, and ultimately assess the effectiveness of the developed model.

Ensuring road safety and minimizing traffic danger is a critical concern for urban planners, engineers, transportation officials, and municipal authorities. Traffic crashes can result in loss of life, injuries, property damage, and significant economic costs for all road users, including pedestrians, cyclists, and motorists. The World Health Organization's (WHO) Global Status Report on Road Safety indicates that road traffic injuries claim the lives of more than 1.19 million people each year, making it the ninth leading cause of death for people of all ages (WHO, 2023a). Pedestrians and cyclists account for more than half of all fatalities. If a street environment prioritizes the safety needs of vulnerable road users, it is likely to also provide a high degree of protection for other age groups with respect to traffic danger (Constant & Lagarde, 2010). Children are particularly vulnerable due to their reduced experience, physical and mental abilities, as well as their smaller size, which not only impacts their ability to be seen or to see, but also increases their risk of injury severity, head injuries, and fatalities (Abdollahi et al., 2023; Cloutier et al., 2021). In Canada, generally motor vehicle traffic fatalities are the third leading cause of death among children between the ages of 1 and 19 (TransportCanada, 2021). To effectively address traffic danger issues across living environments and not only where a crash happens to occur, it is crucial to accurately measure and assess the level of traffic danger at a granular, street-by-street level, with a particular emphasis on protecting vulnerable road users. By prioritizing their needs through urban design, municipalities can create safe systems that account for the limitations of all street users while minimizing exposure to high traffic risks.

Existing studies on traffic danger have primarily relied on analyses of historical crash data, traffic engineering techniques (such as road geometry modifications, speed limit enforcement), and observational studies. As an example, Harirforoush and Bellalite (2019) consider the crash hotspot to find the problematic traffic danger location. Historical crash data can only examine where a crash (the outcome of traffic danger, not the source) occurred. A crash between a vehicle and a pedestrian is highly unlikely if no (or very few) people walk there because of the traffic danger. As a result, traffic danger of streets cannot be accurately measured based on this approach. Observational approaches that include near misses can better highlight danger that did not result in a crash, but also suffer from the problem previously mentioned that a lack of users does not mean that traffic danger is low, though it might mean that risk is low. As such, a means of estimating traffic danger is needed to help inform interventions to improve not only safety, but also accessibility.

Some of the previous traffic danger assessment methods are often based upon biased assumptions that neglect or ignore some dimensions because they overlook a variety of stakeholders during the assessment process thereby excluding their experience and views about traffic danger. In many cases, such approaches also fail to recognize the interaction between different factors related to traffic danger or in some cases the non-linear nature of these relationships. Such approaches also fail to recognize the interaction between different factors in relation to traffic danger or that the relationships are non-linear. A more holistic and multidisciplinary approach is required to develop a framework that assesses traffic danger more accurately. In such cases, multicriteria decision aiding (MCDA) can be beneficial. This is a collection of methods designed to help individuals or groups make decisions that matter by taking into account multiple criteria (Belton & Stewart, 2002). Like all other decision aiding approaches, the MCDA process is there to support rather than replace decision makers.

This study aims to address the limitation of previous approach by proposing a multicriteria decision aid (MCDA) framework to assess traffic danger. It was developed through numerous workshops, on a consensual basis, among different groups of stakeholders who participated in the project. The evaluation model is obtained using the MACBETH method (Bana e Costa & Beinat, 2005). By engaging stakeholders, including experts, parents, and children, through focus groups and workshops, the study constructs cardinal (interval-level) scales and weights for various criteria influencing traffic danger on street segments. The MACBETH multicriteria method is employed, coupled with GIS software for visual representation, to generate aggregated traffic danger scores for street segments in the City of Montreal.

Literature Review

- **Traffic danger definition**

Due to the lack of distinction between traffic danger, exposure and crash risk in the literature on traffic danger, and because risk and exposure may have independent effects on crash incidence, it is necessary to begin this review by clarifying these terms. Traffic danger refers to the inherent risk present in the roadway environment due to factors related to the built environment (such as road design, traffic volume, and vehicle speeds) and personal characteristics such as driver behavior (Widener & Hatzopoulou, 2016). Exposure quantifies the amount of time or distance that road users spend in potentially hazardous conditions, such as the number of pedestrians crossing a busy intersection or cyclists riding on a particular street. Previous studies have primarily considered the influence of exposure on the frequency and severity of collisions, with varying results. For example, (Gropp et al., 2013) reported significant positive associations between exposure to traffic and child pedestrian collisions, while (Rothman, Macarthur, et al., 2014) found no relation between pedestrian exposure and the number of collisions.

Crash risk is the probability of a crash occurring, influenced by both the collision rate and the exposure of road users to these dangers. In other words, risk relates to the likelihood of a crash event occurring (Merlin et al., 2020). It is often measured in rate terms, such as the number of crashes per population size (e.g., road fatalities per 100,000 inhabitants) or per amount of travel (e.g., road fatalities per billion vehicle kilometers traveled) (OECD, 2014). To sum up, while traffic danger focuses on the hazardous conditions themselves, exposure highlights the extent to which road users interact with these conditions. Crash risk combines both aspects to estimate the likelihood of an actual crash. By distinguishing these concepts, it becomes clear why merely analyzing crash data can be misleading—high danger areas might show few crashes simply due to low exposure, rather than an absence of risk. Therefore, a comprehensive approach is necessary to effectively assess and address traffic danger.

Traffic danger has been addressed in a variety of ways. For crashes involving vulnerable users, researchers have focused on two distinct avenues of inquiry: the relationship between traffic and built environment characteristics and pedestrian/cyclist collisions or injuries, and the perceptions of active transport safety by parents and children in relation to the built environment (Amiour, Waygood, & van den Berg, 2022; Cloutier et al., 2021; Rothman, Buliung, et al., 2015). The built environment plays a crucial role in shaping the traffic danger, with factors such as street design, traffic features, and active transportation infrastructure exerting significant influence (R. Ewing & E. Dumbaugh, 2009; R. Mitra, 2013; Rothman, Macarthur, et al., 2014).

The impact of built environment features on crash risks in urban areas has been extensively studied (Asadi et al., 2022; R. Ewing & E. Dumbaugh, 2009; Miranda-Moreno, Morency, & El-Geneidy, 2011). Street design issues such as visibility problems, pedestrian facilities shortages, and lack of traffic calming measures were frequently linked to higher number of crashes. Researchers have found that road characteristics such as street width, lanes, and lighting conditions play a large role in pedestrian crash rates (Xiao et al., 2024), as well as pedestrian exposure (Asadi et al., 2022). Street width, lanes and lighting conditions all relate to traffic danger while pedestrians using that street relate to vulnerable user exposure. The two combine to create crash risk.

Various factors impact traffic danger. Traffic volume is often considered the most significant, with higher volumes linked to increased collision frequency (how often collisions occur within a given time or area) and injury severity (Kim et al., 2022; Miranda-Moreno, Morency, & El-Geneidy, 2011). For example, street segments and intersections with higher traffic volumes see more pedestrian-vehicle collisions and fatalities (Miranda-Moreno, Morency, & El-Geneidy, 2011; Ukkusuri et al., 2012). Studies also explore the relationship between pedestrian volume and collisions. Some suggest that more pedestrians reduce vehicle speeds and thus traffic danger (Thakur & Biswas, 2019), while others are inconclusive about whether this is a causal relationship or a statistical correlation (Elvik & Bjørnskau, 2017). However, accurate pedestrian volume data is often unavailable at the road level, leading researchers to use alternative measures like population density (Cloutier et al., 2021).

High vehicle speeds are a significant risk, with lower speed limits on residential roads resulting in fewer collisions and less severe injuries (Sheykhfard et al., 2021). Speed and traffic volume interact, with increased volume initially maintaining but eventually reducing speeds, which complicates the understanding of their combined effect on safety (Wang et al., 2013).

Land use also influences traffic danger. Commercial areas may increase motor vehicle-pedestrian interactions, raising crash numbers (Clifton & Kreamer-Fults, 2007), while residential areas often provide a protective effect, particularly for child pedestrians (Dissanayake et al., 2009). However, areas with schools and parks generally have higher injury rates (the proportion of injuries that occur relative to the number of collisions) (Bennet & Yiannakoulias, 2015).

Vehicle design contributes to traffic danger, with light trucks and SUVs posing greater risks due to their mass and height, leading to more severe pedestrian injuries (Dragović et al., 2023).

Driver behavior, such as aggressive driving, significantly increases crash rates. Reckless driving behaviors like speeding and failing to yield to pedestrians are major factors in pedestrian crashes (Zafri et al., 2022). Previous studies highlight that aggressive driving styles are closely linked to crash risks (Jun, 2006).Various factors can impact crash risk. According to the majority of traffic safety literature, traffic volume is the most significant factor affecting collision frequency and injury severity (Amiour, Waygood, & van den Berg, 2022; Ziakopoulos et al., 2020). For example, in Morency et al. (2015a), pedestrian-vehicle collisions and fatalities were more likely at intersections with higher traffic volumes. In addition, there have been a number of studies investigating the relationship between pedestrian volume and collision frequency and severity (Cloutier et al., 2021; Elvik & Bjørnskau, 2017; Thakur & Biswas, 2019). While some studies have concluded that it remains uncertain whether the safety-in-numbers effect is a causal relationship or merely a statistical correlation with the frequency of traffic danger (Elvik & Bjørnskau, 2017), others have found that an increase in pedestrian numbers and movement results in reduced vehicle speeds, thereby decreasing traffic danger (Thakur & Biswas, 2019). However, due to the lack of readily available pedestrian volume data at the road level—this data is typically available at a larger scale—previous studies have often not considered it or have used alternative measures such as population density (Cloutier et al., 2021). Another study found that child pedestrian collisions are more likely on large and straight roads with high traffic volumes (Rothman, Buliung, et al., 2014). However, the frequency of collisions should not be the only focus as the severity is a critical consideration. High vehicle speeds pose a significant risk to pedestrian safety since they increase the risk of injury or death (Sheykhfard et al., 2021). Researchers found a 28% reduction in pedestrian-motor vehicle collisions when speed limits were lowered on Toronto's residential roads from 40km/h to 30km/h (Fridman et al., 2020). High speeds are associated with a higher likelihood of severe injuries and fatalities in the event of a crash (Elvik et al., 2004; Ukkusuri et al., 2012), which implies higher traffic danger. However, as confirmed by various studies, changes in speed levels are related to changes in traffic volume. According to (Wang et al., 2013), when traffic volume increases, speed initially stays the same and then decreases. Therefore, accurately considering the relationship between traffic volume and speed is crucial for understanding traffic danger, as the interaction between these two factors can significantly impact safety.

The presence of different land uses is another built environment factor related to traffic danger. Various studies have considered the impacts of different land uses on traffic danger, with mixed findings (Amiour, Waygood, & van den Berg, 2022; R. Ewing & E. Dumbaugh, 2009). One important factor discussed in previous literature is commercial areas. Some research shows that commercial land use is not related to traffic danger (Rothman, Buliung, et al., 2014), while other studies explain that commercial land uses may generate more interactions between motor vehicles and pedestrians, increasing the number of crashes within a specific buffer along each street segment (Clifton & Kreamer-Fults, 2007). Additionally, arterial roads, often associated with commercial land uses, can increase the level of traffic danger (C.-Y. Yu, 2015).

For residential land use, studies have shown a negative relationship with injuries among pedestrians, particularly children. Areas with high residential land use tend to have a protective influence, making them safer places for walking (Dissanayake et al., 2009). Other land uses, such as schools and parks, are generally associated with higher injury rates and increased traffic danger levels (Bennet & Yiannakoulias, 2015). However, there is no significant relation between the presence of industrial zones and traffic danger (Clifton & Kreamer-Fults, 2007).

In addition to street design factors, vehicle design has been acknowledged as part of the problem when it comes to traffic dangers. Despite a lack of specific information regarding vehicle-specific risks for child pedestrians, previous studies have shown that light trucks and sport utility vehicles (SUVs) present a greater risk to adult pedestrians than conventional vehicles because their mass makes braking more difficult, and their height causes more upper body injuries (Desapriya et al., 2010; Hu & Klinich, 2015).

Another critical factor that increases traffic danger is driver behavior and attitudes towards traffic safety. In particular, aggressive driving habits such as speeding, rapid acceleration/braking, and failure to pay attention to pedestrians correlate strongly with higher crash rates (Ellison et al., 2015). According to (Zafri et al., 2022), 90% of pedestrian crashes occurred due to reckless driving behavior by motorists with no intention to yield to pedestrians. Researchers have consistently concluded that the failure to follow crossing and yielding laws are strongly associated with crashes involving pedestrians (Ulleberg & Rundmo, 2003). Jun (2006) examined patterns of speeding, acceleration, and braking using in-vehicle GPS and diagnostic data to predict crash involvement. These individual behavioral measures correctly predicted 68% of crash-involved drivers and 87% of non-crash-involved drivers, highlighting the link between aggressive driving styles and crash risks. If driver yielding behavior does not align with pedestrian expectations, it results in an unsafe crossing situation that can lead to collisions and injuries (Ulleberg & Rundmo, 2003).

To better understand traffic danger assessment, it is essential to define it accurately. Traffic danger refers to the hazards associated with road traffic that can potentially cause harm, injury, or loss to road users (Widener & Hatzopoulou, 2016). In this study, traffic danger assessment involves identifying the factors that contribute to traffic danger and determining the relative importance of these factors The assessment of traffic danger can identify high-risk areas, evaluate safety interventions, and prioritize resources to improve road safety.

Previous studies primarily assess traffic danger by evaluating the probability of collisions and calculating the likelihood of different types of collisions, such as fatalities and severe collisions. These assessments typically focus on quantifying the risk of crashes (collision rate) and the potential severity of their outcomes. (Lakim & Ghani, 2022). The assessment of traffic danger can identify high-risk areas, evaluate safety interventions, and prioritize resources to improve road safety (Arun et al., 2021). The literature contains many methods for assessing traffic danger. In some cases, predictive and simulation modeling are used with a variety of software (Lakim & Ghani, 2022). By using statistical, mathematical, or machine learning techniques, proponents propose that these techniques can predict future crashes and identify locations with elevated risk levels (Zheng & Sayed, 2020). To predict crash frequencies and decide where to invest in safety, models like Safety Performance Functions (SPFs), Empirical Bayesian methods, and machine learning algorithms are used. These models analyze crash data, road features, traffic volume, and other factors. (Li, 2020). Archer and Young (2010) analyzed and predicted risk of collision based on three two proximal indicators: time-to-accident, time-to-collision, and post-encroachment. In another study, Sobhani et al. (2013) used a micro simulation model to evaluate the performance of roads in terms of danger by estimating the number and the severity of conflicts. Another assessment method involves physical observation on site or video observation at the office. In Ambros et al. (2014) study, observers spotted conflicts at a selected intersection and classified them by conflict type and severity. While these studies are useful and advanced in assessing the risk of collisions, they fail to consider in depth what causes traffic danger and what factors can exactly influence traffic danger. As a result, the definition of traffic danger is directly related to the incidence of collisions and analysis of possible conflicts. While these methods are valuable, they often rely heavily on historical crash data and results of simulation models. These models may fail to capture the multifaceted nature of traffic danger, particularly near-misses and unreported crashes. These methods are also often resource-intensive and may not provide a comprehensive view of the interactions between various risk factors. Additionally, focusing solely on crash statistics ignores the other impact of traffic danger that leads to stress and limits users' rights to move around safely. It is essential to recognize that no crashes between pedestrians and vehicles would occur if streets were so dangerous that no pedestrian would walk there. Moreover, these methods also avoid considering the perspectives of various stakeholders, such as local communities, traffic planners, and policymakers, along with perceptions of safety among road users, which can greatly impact traffic danger measurement.

Considering these limitations, there is a pressing need to develop more comprehensive methodologies for measuring traffic danger. Multicriteria decision aiding (MCDA) is emerging as a promising alternative to determining safety measures by considering various criteria (Wang et al., 2009).

Recently, incorporating stakeholders' opinions has become increasingly popular in transport planning (Donais et al., 2019b; Macharis & Bernardini, 2015; Marleau Donais et al., 2019). In traffic danger assessment, several studies have employed MCDA techniques, most notably using the Analytic Hierarchy Process (AHP) approach. For example, Dano (2018) developed a traffic safety model for Saudi Arabia based on expert-based questionnaire surveys and Analytic Hierarchy Process (AHP) to rank a set of road safety variables by incorporating policymakers' preferences. TOPSIS methodology was similarly used to assess traffic danger by comparing alternatives to ideal and worst-case scenarios. The TOPSIS-RSR methodology was developed by (Chen et al., 2015) in order to evaluate the road safety risk based on traffic danger indicators derived from various literature reviews. Prior studies ignored the relationships between several factors that influence traffic danger and sometimes did not account for the varying impact of different intervals within each factor. For example, a change in speed from 20 to 30 km/h may have a different effect on traffic danger compared to a change from 30 to 40 km/h, yet this distinction was not always considered. Further, indicators used to determine traffic danger were mostly based on literature, without considering stakeholders' experience and views. Furthermore, Regarding most common MCDA methods in traffic danger , TOPSIS is appropriate for quantitative and cardinal data and cannot take into account qualitative data (Çelikbilek & Tüysüz, 2020). As for AHP, although very popular and widely used, it suffers from many shortcomings (Munier et al., 2021) such as assuming criteria independence and their limitation in evaluating large number of alternatives. Existing MCDA studies often overlook fundamental aspects, such as considering the interactions among different variables and defining the scales for various levels of criteria, emphasizing the need for more comprehensive approaches. This paper proposes an approach to respond to this issue.

The purpose of this study is to address the complexity of assessing traffic danger through methodologically sound MCDA techniques. Our goal is to develop an evidence-based tool that accurately assesses traffic danger with focus on children as a vulnerable group by examining the views of stakeholders.

Methodology

6.1.1 Framework

Our multicriteria danger evaluation model is built using the MACBETH multicriteria method (e Costa & Vansnick, 1994), coupled with GIS software ArcGIS Pro 3.0.2 (Esri, 2022) for visual representation. MACBETH constructs interval-level scales from participant judgments, determining weights and generating aggregated scores for alternatives. This established method employs a constructivist approach, engaging stakeholders through workshops to minimize conflicts and achieve consensus. Although MACBETH has been used in a variety of applications to assess transport related projects (Donais et al., 2019b), it has not been applied to traffic danger and its use in classifying street segments according to traffic danger is unique. I chose to use MACBETH primarily due to the complexity of measuring traffic danger. Given the numerous variables that influence traffic danger, and their unequal and non-linear effects, MACBETH effectively accounts for all these aspects. MACBETH makes it possible to calculate an aggregated danger score based on a weighted mean for each street segment (Abi-Zeid, et al., 2023). The research framework comprises five phases: (1) problem structuring, (2) constructing local danger scales for each criterion, (3) weighting criteria, (4) generating a global geographical traffic danger index maps, and (5) validation. Each phase involves multiple steps, detailed in Figure 6.1 which will be described below.

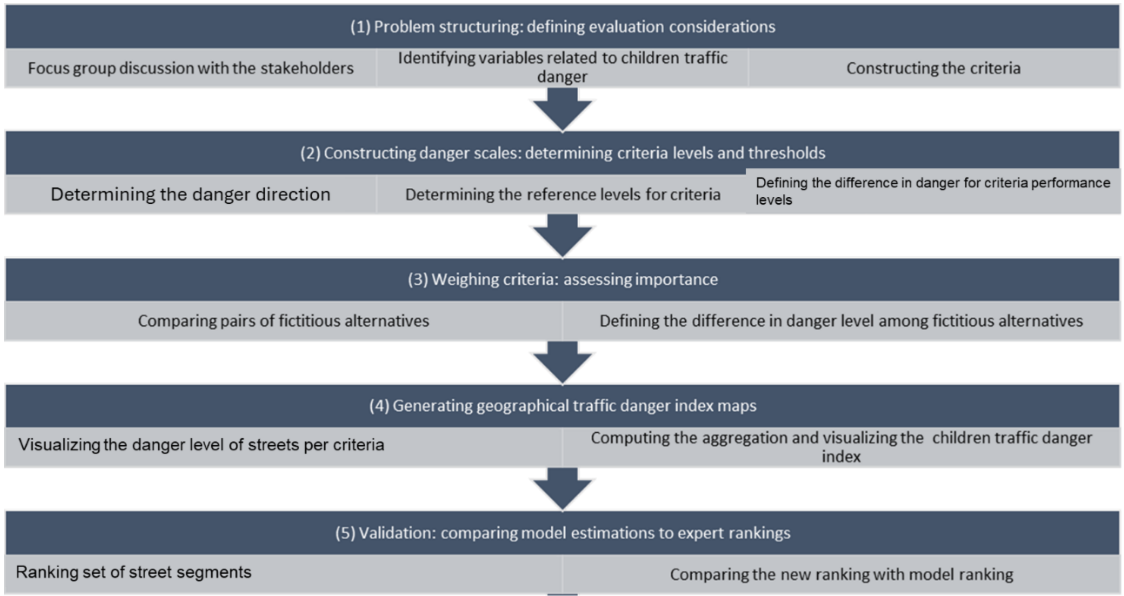

Figure 6.1 Overview of framework (inspired by (Donais et al., 2019b)

6.1.2 Application

The framework was applied through online group and subgroup workshops involving three key stakeholder types: experts, parents, and children. These workshops were conducted via Zoom (Zoom, 2024) between May and June 2023, accommodating participants' schedules. A total of six focus groups were held: three with experts (primarily in English, given their diverse North American locations), two with parents (one in French, one in English), and one with children (in French, the dominant language of Montreal). The expert group included public health professionals, engineers, city officials, and urban planners. The research team served as facilitators during the workshops, without attempting to influence the decisions. Their purpose was to clarify the process and facilitate the discussion process.

- **Structuring the problem**

The MCDA process starts with problem structuring (see Figure 6.1), involving problem identification, criteria construction, and scale establishment through collaborative group workshops. Participants in focus group workshops were queried about their views on traffic danger, exploring influencing factors and their relationships. A unique questioning strategy and interview guide was developed for each stakeholder group based on their unique characteristics. A detailed account of the focus groups can be found in Abdollahi et al. (submitted). The two key questions for the focus groups were essentially:

1) **"What are the most important factors affecting traffic danger?"**
2) **"Are there other factors that specifically affect children's traffic danger?"**

Using thematic analysis, nine categories were identified from the focus group discussions: Vehicle characteristics, Traffic characteristics, Active transport infrastructure, Visibility, Traffic calming, Street design, Land use, Behavior, and Seasonal effects. From the discussions, several of the categories were combined as they interact with each other to create six criteria to assess traffic danger (5 qualitative criteria and one quantitative)

Next, we defined the performance levels of each criterion in sub-workshops and with the experts in the research team. It should be noted that the significance of different levels of criteria was identified through focus group discussions. For example, participants stated that as vehicle speeds exceed 30 km/h, their contribution to traffic danger increases significantly. As a result, we highlighted this speed threshold in combination with other relevant variables within this criterion.

These were often a combination of measurements related to one or more indicator. As an example, I used the indicators number of street lanes and the presence of trees to determine the ordinal performance levels of Driver's visibility. As a result, the following three performances defined the scale for this criterion:

Low visibility: one lane with trees or two lanes with trees,

Medium visibility: 3 lanes with trees, or 1 or 2 lanes without trees.

High visibility: 4 or5 lanes with trees or 3 or 4 or 5 or6 lanes without trees.

Appendix B contains details of the performance levels of all the criteria. Table 6.1 presents the criteria and the performance levels.

- **Constructing cardinal danger scales**

In this phase of the analysis, I use the MACBETH method in order to transform the criteria's performance levels into danger levels based on participants perceptions, experience and knowledge. I conducted subgroup meetings with experts to build the danger scales for each criterion by asking participants: (1) first, to specify the danger direction (meaning whether a smaller or a larger value on the criterion makes the danger higher), (2) defining performance levels of criteria, (3) defining a reference level of traffic danger that is “lower” and “higher” in order to define a criterion’s unit, and (4) expressing the perceived level of danger difference between two performances, necessary for constructing an interval scale. As an example, Figure 7.2 shows the danger scale built with the participants for Points of interest and commercial area size. As is almost always the case, the built interval scale is not linear (Abi-Zeid et al., 2023).

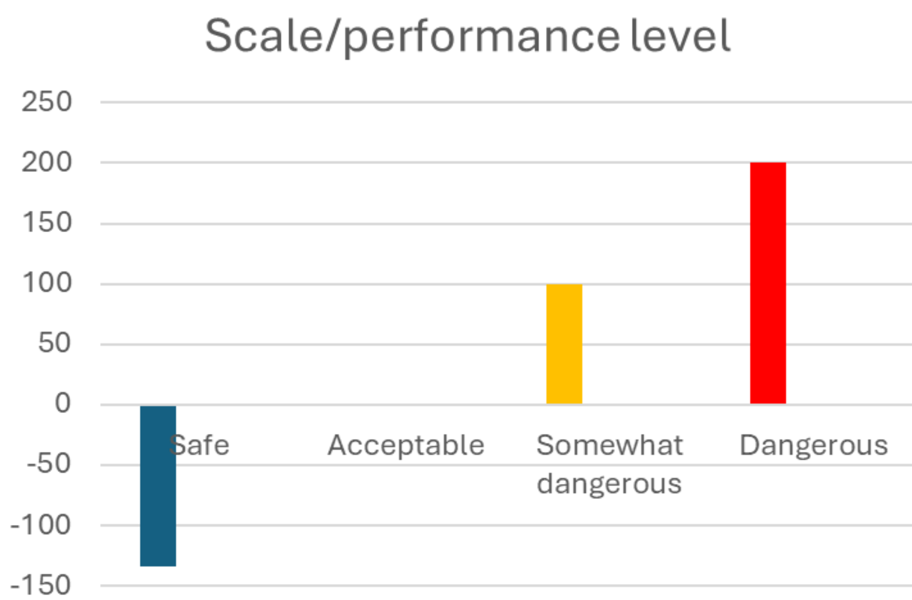

Figure 6.2 Constructed danger scale for Presence of points of interest & commercial area size

Figure 6.2 shows different performance level on the x-axis and the MACBETH scale on the y-axis. It should be noted that the measure combines the number of Points of Interest (POI) and the size of commercial areas (categorized as small, medium, and large). All possible performance variations within the study area have been considered. In order to define a unit for each criterion, reference levels must be provided. For this criterion, a “higher” reference level, somewhat dangerous, refers to a street segment that participants would consider dangerous (it could be said that at that point participants start getting concerned about the traffic danger created by this criteria). In the case of the "lower" (neutral) reference level, acceptable, relates to a level that is at the lower limit of danger. At this level, the criteria is considered neither safe, nor dangerous. By convention, the lower level is assigned a value of 0 and the higher level a value of 100. The danger scales are open, meaning that it is possible to have negative danger values or values higher than 100. So, a unit is 1/100 of the difference between the danger of the higher reference and that of the lower reference. Table 6.1 presents the lower and higher reference level of all criteria.

Table 6-1 Criteria Reference Level

Criteria	**Lower level**	**Higher level**
Traffic-design characteristics	Acceptable (e.g., speed limit =30 km/h, traffic volume = low, two-way street- one lane)	Some-what dangerous (e.g., speed limit = 40 km/h, traffic volume= low, one-way street, 2 lanes)
Traffic calming	Very good effect (e.g., a street with a bollard and an in-street sign)	Some effect (e.g., a street with an in-street sign)
Point of Interest (POI) and Commercial Size	Acceptable (e.g., 3 POI with small size commercial area)	Some-what dangerous (e.g., 4 POI with medium size commercial area)
Driver's Behavior	Acceptable (e.g., adequate respect to speed limit and stop sign and moderate disrespect to traffic signal)	Some-what dangerous (e.g., moderate disrespect to speed limit and adequate respect to stop sign and traffic signal)
Driver's Visibility	Low visibility (e.g., two-lane street with trees)	Medium visibility (e.g., three-lane street without trees)
Heavy vehicle characteristics	50 veh/day (one vehicle every 20 minutes)	300 veh/day (one vehicle every 3 minutes)

In addition, participants rated the perceived differences in danger between each performance level based on a 7-point semantic scale: null, very weak, weak, moderate, strong, very strong or extreme by comparing each pair of performance levels of each criteria. This information is crucial in order to construct an interval scale that will allow us to aggregate local criteria danger levels into a global score using a weighted sum.

- **Details of criteria**

Traffic-design characteristics

This criterion defines segment performance based on four factors: street segment direction, speed limit, traffic volume, and number of lanes for each segment. The data for speed limit and direction were extracted from Open Data Montreal (OpenDataMontreal, 2023). The volume of traffic was estimated based on Average Annual Daily Traffic (AADT). For the Average Annual Daily Traffic (AADT), since this data is not available for all street segments in the study area, we utilized the results from a previously developed simulation model at Polytechnique Montréal. Open Street Map data was used for the number of lanes. During the workshop with the research team, a Traffic design characteristics criterion was developed with five performances: 1.) Safe; 2.) Acceptable; 3.) Somewhat Dangerous; 4.) Dangerous; and 5) Very dangerous. In terms of the direction of the criterion, if everything else is equal, the higher the level, the more dangerous the street segment. As part of our model, I also placed "acceptable" as the lower level and "somewhat dangerous" as the upper level. As a reminder, the lower level is the point at which criteria is neither safe nor dangerous. The upper level is where one begins to get concerned about traffic danger.

Traffic calming

Using this criterion, segments are ranked according to whether they have traffic calming measures and, if so, how many and what types of traffic calming measures they have (see Table 2). Based on the data provided by the City of Montreal, the following categories have been defined: 1) segments without traffic calming measures; 2) segments with very little traffic calming effect; 3) segments with some traffic calming effect; and 4) segments with very good traffic calming effect. Additionally, streets with very good traffic calming effects were placed at the lower reference level, whereas those with some effects were at the upper reference level. Assuming other factors are equal, a higher traffic calming value will result in lower traffic danger levels.

Point of interest and commercial size

In order to illustrate the influence of land use near a segment, the participants decided to use points of interest. Points of interest (POI) are special places or areas within urban environments that are unique, important, or relevant to the community (Psyllidis et al., 2022). In the case of the City of Montreal's open data, the list of POIs is extensive including cultural and recreational facilities, transport hubs, healthcare facilities, etc. In focus group discussions with participants, commercial areas were of far more concern than any other POIs, especially when the commercial land use is larger, since this can increase pedestrian-vehicle interaction. Thus, I decided to separate the commercial from the other POIs and measure their area as a factor in this analysis.

First, I spatially extracted the commercial areas from the other Points of Interest (POIs). Then, after calculating the area of each, I spatially joined each commercial area to the nearest street segment. To be more precise, I classified the commercial areas into three categories: small, medium, and large. As for the other POIs, I counted the number of POIs near the street and classified the result as low, medium, or high. With respect to traffic danger, four main levels were identified: 1) Safe, 2) Acceptable, 3) Somewhat dangerous, and 4) Dangerous. As a result, level 2 (Acceptable) was the lower reference level and level 3 (Somewhat dangerous) was the upper reference level. When all other things are equal, streets with the higher level of this criteria have a greater level of traffic danger.

Driver’s Behavior

Drivers' behavior can affect traffic danger in many ways (Sheykhfard et al., 2021). While there are many factors to consider when developing this regulation, based on the results of the focus group discussions, I decided to focus on drivers' respect for traffic control and speed limits. In order to gather this information, I designed a survey and distributed it to residents on the island of Montreal asking different questions regarding the behavior of drivers. The questions related to these three key behaviours: speed limit respect, stop sign respect, and traffic signal respect. A detailed descriptive analysis of the survey and the survey’s participants characteristics questions can be found in Appendix C and Appendix D respectively. Next, I introduced four different scales to facilitate creating the performance level: strongly respect, adequately respect, moderately disrespect, and strongly disrespect. At the meeting of the subgroup, the following levels were constructed based on combinations of the scales for the three key behaviors: 1) Safe, 2) Acceptable, 3) Somewhat dangerous, 4) Dangerous for this criterion. According to these levels, 'Acceptable' is defined as a lower level, while 'Somewhat dangerous' is defined as an upper level. When all other factors are equal, higher levels result in more traffic dangers.

Visibility

Another factor that participants mentioned during focus group workshops was driver visibility, which can be influenced by architectural features or obstructions. Participants stated that limiting driver visibility could reduce traffic danger by concentrating their attention more closely and reducing their speed at the segment level. In order to evaluate this criterion, I decided to combine two factors: the number of lanes on each street segment and the presence of trees on the street segment. Using the data available, three performance levels were defined: 1) low visibility, 2) medium visibility, and 3) high visibility. It was decided that the lower level would have low visibility and the upper level would have medium visibility for this calculation. All other criteria are equal, higher visibility levels resulted in greater traffic risk.

Heavy vehicle characteristics

All focus groups recognized the dangers associated with larger vehicles, such as SUVs and trucks. Larger vehicles have larger blind spots, which can obscure pedestrian visibility, particularly for children (Edwards & Leonard, 2022). In order to create this criterion, I used a measure of the number of trucks (light such as delivery trucks and heavy) and buses that pass along each street segment. Due to the lack of data for all street segments in the city of Montreal, I estimated the heavy vehicle volume with the help of the built environment and the design characteristics of the segments using Light Gradient Boosting Machine (LGBM) which is similar to the LGBM model used by Naseri et al. (2022). I use this criterion as the only quantitative criteria in our model. In terms of the reference levels, 50 vehicles per day was the lower level and 300 vehicles per day was the upper level. There is a greater danger of traffic when the heavy vehicle volume is higher.

- **Weighting criteria: deriving scaling constants**

In order to determine the weighted aggregated average for each alternative (street segment), the weights (scaling constants) of the criteria must be determined through input from the participants. The weights are elicited by comparing pairs of fictitious alternatives. The alternatives are built in such a way that all criteria are at the "lower" reference level except for one criterion with an "upper" reference level. The number of fictitious alternatives (scenarios) is as great as the number of criteria (6 in our case) plus one alternative where all criteria are scored with the "lower" score.

For this step, two separate meetings with 3-5 experts were organized. As this process requires more discussion and takes time, smaller groups were preferred. The experts were asked to compare each pair of fictitious alternatives. For each pair, the group chose the segment they believed was more dangerous and qualified the difference in danger level using the MACBETH semantic scale (starting from no difference to extremely different). In the example presented in Figure 3, the group decided that segment A with a heavy vehicle volume of 300 vehicles per day and low visibility was more dangerous than segment B, which had a heavy vehicle volume of 50 vehicles per day and medium visibility. All other criteria were at the lower limit and assuming additive difference independence, do not influence the assessment of danger (Dyer, 2016). Next, the group came to the consensus that the difference in danger between the two alternatives was "moderate-strong". In total, we conducted 15 comparisons of fictitious alternatives to determine the weights of the criteria. Figure 6.3 illustrates an example of this step.

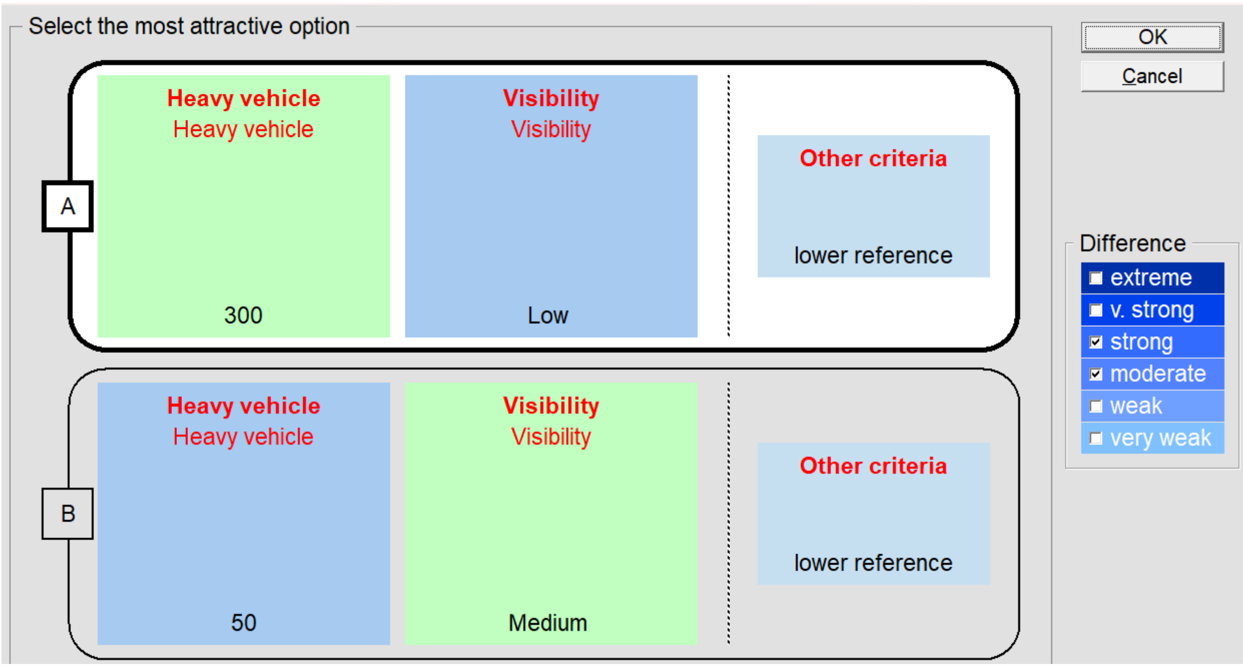

Figure 6.3 Example of an analysis of two fictitious segments

- **Producing Traffic Danger Score maps**

Data

This study relies on primary data obtained from Montreal, sourced from shapefiles on the Open Data Montreal portal (OpenDataMontreal, 2023). The dataset includes geolocated criteria which includes the measurement of each criteria. Details of data and measurement can be found in Appendix H. To address driver's behavior, a survey tailored to the City of Montreal was conducted. It is important to note that the study's analysis is confined to some neighborhoods of the City of Montreal due to a scarcity of comprehensive data on traffic safety measures and destinations, despite the existence of other municipalities on Montreal Island.

This phase combines MCDA with GIS to process data, incorporate spatial information, assess street segments, and arrive at the final ranking. During this process, maps are produced to better visualize participants' views and the results. In order to interface the MACBETH model with

ARCGIS, a software for automatic data processing and transfer was used (Marais, 2021). This software was recently expanded into an application called Othello, available as open source on Github at https://github.com/ulaval-rs/othello. In addition, it allows decision makers to gain a broader perspective on a large amount of data. It is important to note that three functions are performed in the procedure for spatial multicriteria problems: finding the most accurate measure based on the available data, aggregating the spatial data, and aggregating the multicriteria data.

- **Validation**

Validating the constructed models is essential to ensure they reflect the knowledge of the participants. This was accomplished by comparing a model's ranking of 17 street segments (three for each danger class, the street with lowest danger score and the street with highest danger score) with ad hoc rankings provided by participants. A random set of alternatives (real street segments in the study area) was selected for the purpose of representing a wide range of contexts and included two fictitious alternatives, namely, an all "lower" alternative and an all "upper" alternative. In order to facilitate the ranking process, I categorised the street segments into 5 categories from safe to very dangerous, without explicitly naming them. A list of random streets was presented to the group during the meeting, and then they were asked to assign the alternatives to one of 5 categories based on their opinions. Whenever there was a difference of view about a street segment, they were asked to explain it. Our model was validated since more than 80% of segments (14 segments) are categorized in the same order as the MCDA model.

Following that validation process, web-based interactive maps of the study area were prepared and sent to experts who were familiar with the City of Montreal to test for any issues. Upon clicking a street, the street danger score and level were displayed, as well as the street name and segment ID. Experts were asked to check the streets, with which they are more familiar with and see if their expectation of danger level matches the ranking produced by the model.

Results

There are more than 41,000 street segments in the City of Montreal. Analysis was limited to the segments of the selected borough, for almost 27,000 street segments. Due to data missing for many criteria, segments outside the study area were excluded. Figure 6.4 shows the study area.

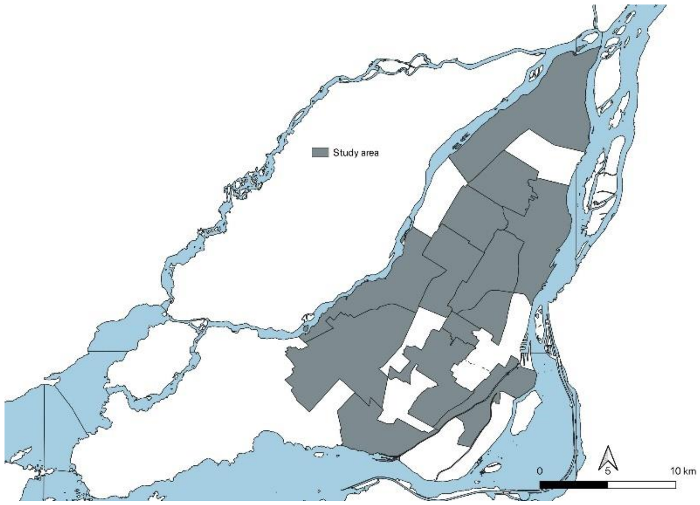

Figure 6.4 Study area

The results are presented as maps depicting street networks for each of the six criteria (Figure 6.5). The color scale indicates the degree of danger from safe to very dangerous. In between these two extremes, street segments in class 2 near the lower reference level take on blue shade, and those near the upper reference level take on a orange shade. In addition, the black segments are segments that weren't studied. Criteria maps reveal that the performance values for a segment can vary significantly depending on the criteria used. In some criteria maps, street or segment measurements are different based on a smaller scale (e.g. Traffic-design characteristics), but in others, the measures appear to be taken at a broader scale, particularly within areas that encompass more than one street or segment (e.g. the presence of commercial areas and points of interest).

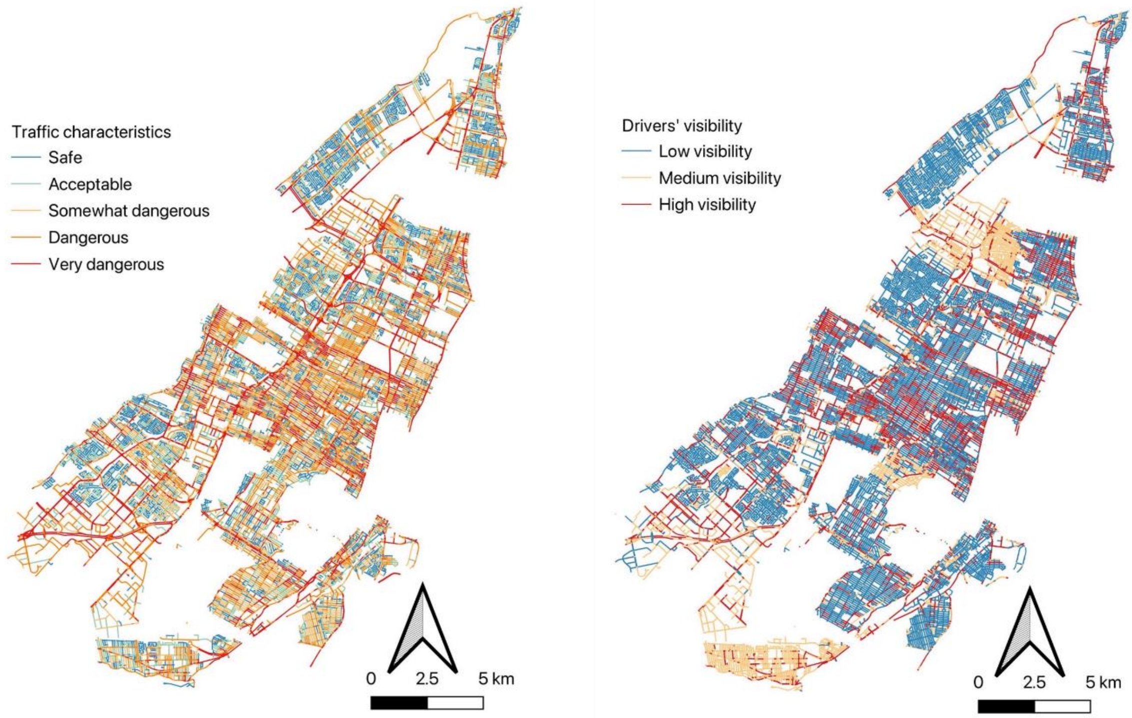

Figure 6.5 Segment criteria

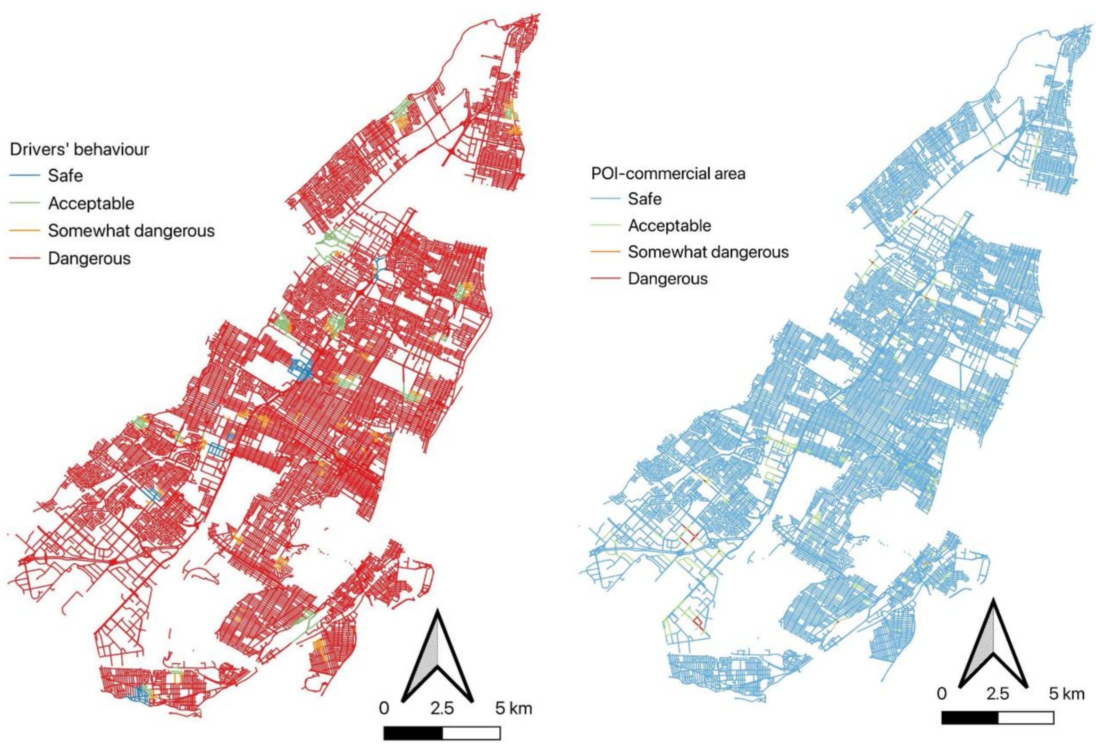

Figure 6.5 Segment criteria (continued)

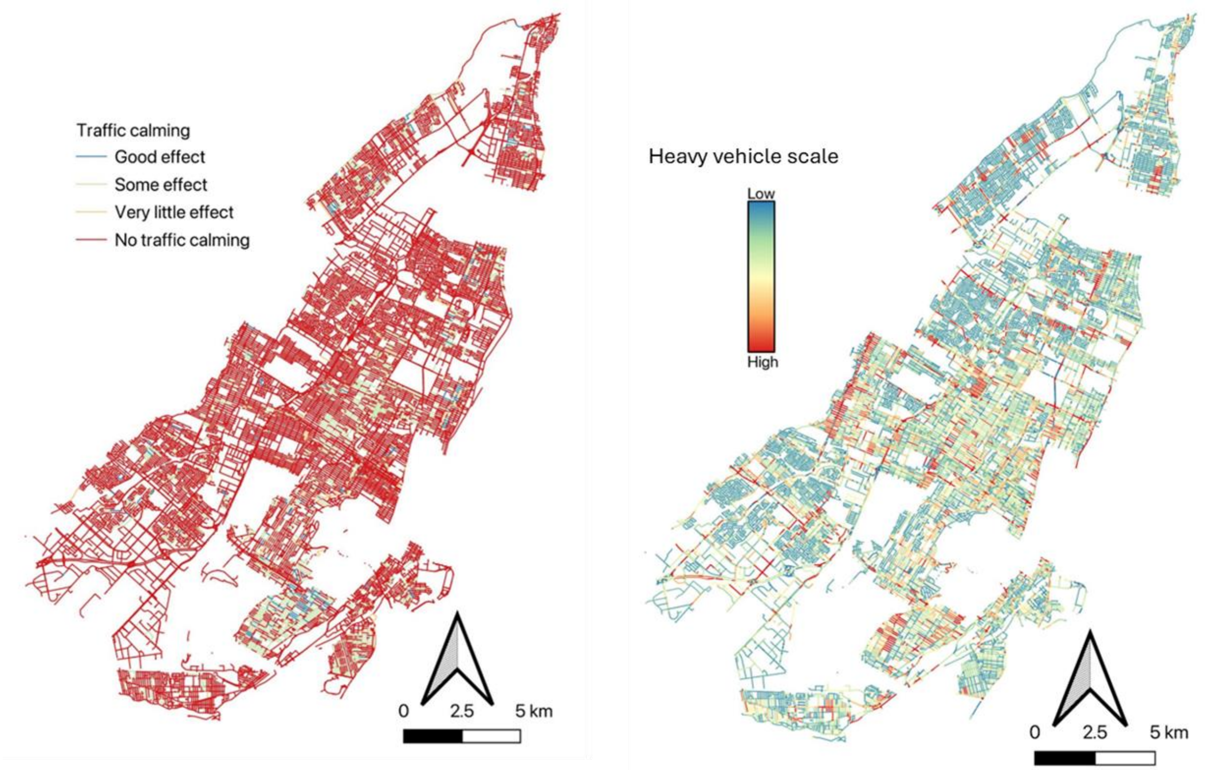

Figure 6.5 Segment criteria (continued)

Using aggregated results, Traffic danger scores can be compared between different streets in the study area. Figure 6.6 shows the 'Traffic Danger Score' (TDS) Using natural breaks in GIS, I classified the dangerous scale into five different groups: Safe, Acceptable, Somewhat Dangerous, Dangerous, and Very Dangerous. The numerical traffic danger scores were grouped to make comparisons between different streets more understandable. The natural breaks method was chosen because it identifies the best arrangement of values into classes by minimizing the variance within each class and maximizing the variance between classes, ensuring a more accurate and meaningful categorization of traffic danger levels. This grouping was validated through workshops with experts. Additionally, they are presented at the borough level in the study area.

Figure 6.6 Traffic Danger Score

In addition, the frequency of each traffic danger category in city level can be seen in Figure 6.7.

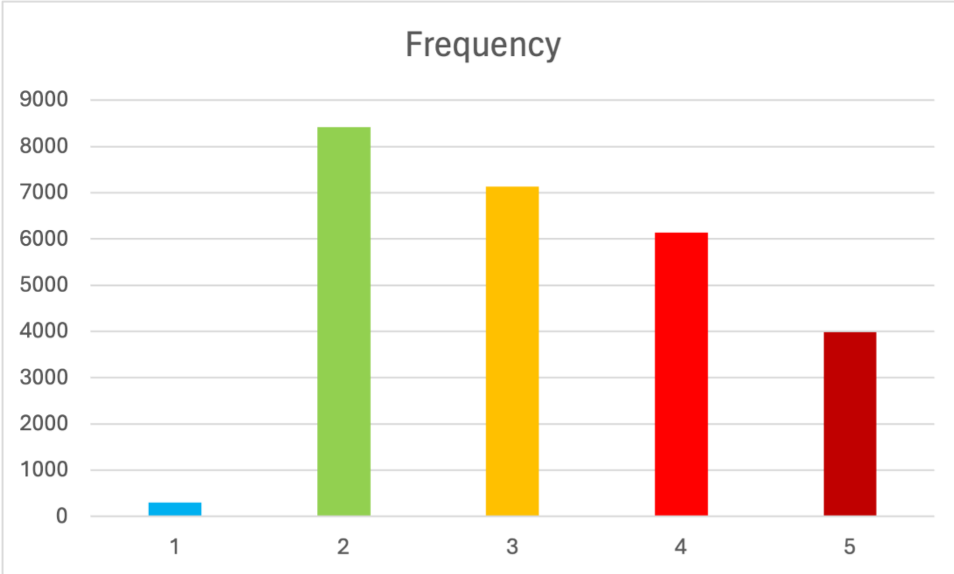

Figure 6.7 Frequency of different danger class (1: Safe, 2: Acceptable, 3: Somewhat dangerous, 4: Dangerous, 5: Very dangerous)

Apart from comparing traffic danger between neighborhoods, I chose to analyze segments relative to other segments within that neighborhood. As a first approach, I compared the proportion of different danger classes by neighborhood are shown in in neighborhoods. The frequency of different street danger level is shown in Figure 6.8. The proportion of the two most dangerous segment categories vary from just over 25 % in to nearly 50 %. A potential interesting comparison is found in the center with one borough (Outremont) having a relatively small proportion of those top two while its neighboring area has nearly 50 % (Rosemont- La petite patrie).

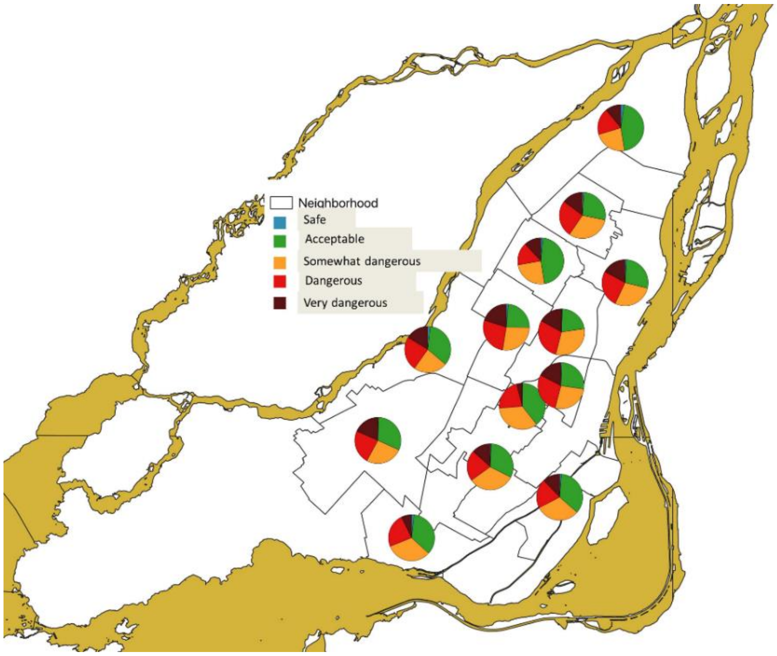

Figure 6.8 Percentage of different street danger class at neighborhood level

Discussion

The purpose of this study is to assess traffic danger with special consideration for children. In our assessment model, I incorporated different stakeholders' perspectives and applied a socio-technical MCDA process to selected boroughs in the City of Montreal. To our knowledge, this is the first instance of a measure of traffic danger as opposed to the risk of collision and further one in which children and parents have been included in the assessment process and their opinions have been considered as key input to the model. Through our participatory approach, I was also able to improve communication among stakeholders and construct danger scales and weight different criteria.

The process was able to identify interactions between factors of traffic danger and create criteria based on those. As an example, the traffic-design characteristics criterion led to classifications of different traffic and design characteristics. Earlier research has highlighted the impact of speed, traffic volume, and street directions on traffic danger (Abdollahi et al., 2023; Cloutier et al., 2021; S. A. Richmond et al., 2022; Rothman, Buliung, et al., 2014), but the majority of existing studies have examined these variables independently without taking into account their interrelationships. According to our knowledge, none of the reviewed papers explored the intricate connections between these variables in relation to traffic danger. In light of this significant gap in the literature and the results of our focus group discussion, I was able through our model structuring phase to identify these interrelationship and develop appropriate criteria.

Previous approaches have considered general land-use measures such as simply “residential”, “commercial”, or “institutional” such as schools (Kim et al., 2022; Lee et al., 2016; Rothman, Macarthur, et al., 2014). Those features are likely related to exposure, acting as generators or points of attraction. However, in this research, the focus was on traffic danger, how each criteria impacted traffic danger. In such a process, the use of buildings immediately adjacent to the street segments were identified as influencing traffic danger. Considering the presence of different points of interest (POI) near one street (e.g., both healthcare centers and schools) can increase the probability of interactions between drivers and pedestrians based on the results of our focus group discussion, consequently increasing the traffic danger. As such, this research went further than previous approaches to connect how urban activities might influence traffic danger.

Previous research has either not considered traffic calming or in a binary fashion (present or not) (Distefano & Leonardi, 2019; Rothman, Macpherson, et al., 2015a; Zalewski & Kempa, 2019). However, not all traffic calming features impact traffic danger to the same extent. As such, the Traffic calming criteria developed here estimates the influence on traffic danger to the number and the type of measures. Thus, this research distinguishes traffic calming interventions by both quantity and quality.

Speeding and disregard for traffic control were identified as critical point of driver behaviour factors influencing the dynamic between pedestrians and drivers. A street might have very similar design characteristics, but for some reason, the driver’s behaviour on the street might be better or worse than other similar conditions. One possibility to measure driver behaviour would be to use infractions. However, police are not uniformly distributed across the network. Complaints from citizens might depend on whether they are sufficiently motivated to report the problem and their belief that doing so will have an impact. In this research, a population representative survey by the FSA area was used to gather a city-wide measure. Using a survey to understand residents' perception of driver behavior, I found that most participants were unsatisfied with drivers' respect for traffic control and speed limits. This finding itself likely highlights the problem of traffic danger and that the culture of driving in the region tends towards dangerous behaviour such as speeding, aggressive driving, or failure to follow traffic rules, which in turn increases the likelihood of traffic related injuries (van Haperen et al., 2019). These findings align with earlier research indicating that speeding and disregard for traffic control are crucial factors in the pedestrian-driver dynamic conflict.(van Haperen et al., 2019) (Chen et al., 2016; Sucha et al., 2017).

This study represents a significant step forward in evaluating traffic danger in urban environments. However, it is essential to acknowledge its limitations to guide future research and practice. Some of these limitations are similar with the previous MCDA and stakeholder engagement processes, as highlighted by Abi-Zeid et al. (2023), such as the complexities of integrating multiple perspectives into decision-making frameworks and challenges in the recruitment process. However, this research also faces its own specific limitations. One of the primary limitations is the reliance on available data from public sources and surveys, which may not fully capture the street design such as lane width. Traffic characteristics variables are not available for every street such as practiced speed (versus legal speed), AADT, the number of large personal vehicles such as pick-up trucks and SUVs, or the number of large and heavy vehicles. The study gave particular attention to children as they are a large part of the population who are more likely to walk than others, they have different characteristics such as being shorter, may have different cognitive competence to adults, and are developing their experience with traveling autonomously. However, some parts of the population may require additional consideration such as some elderly who have physical and cognitive issues that impact their ability to be autonomous (Beauchamp et al., 2022) or people with disabilities (Ross, 2020; Routhier et al., 2024).

As for the parent and child groups, it was difficult to find some problems arose with respect to finding reliable participants who could participate for a few hours. I initially targeted the general public through online advertising on social media and physical announcements in some neighbourhoods in Montreal. Due likely to online advertising and hosting the focus groups online, some participants were not active or were not the right stakeholders, and one meeting with children was canceled as it was not possible to confirm that the participants were in fact children. After contacting different communities, I found reliable participants who actively participated because traffic danger was a concern. One recommendation for similar future work is to not advertise a financial incentive, but to reward those who are internally motivated by the problem (and not by money) after they have volunteered.

The methodology applied in this research has different challenges than is likely experienced when estimating the likelihood of a collision. A key challenge is the time required to achieve the objective. All the participants were new to multi-criteria workshops, so each session required time to explain the procedure and for the participants to fully understand the tasks. In my opinion, the most challenging part of the process was determining the weight of each criterion. To get a more holistic view of traffic danger, intentionally experts with different expertise were recruited. As a result of these different expertise and perspectives, they were often required to discuss the criteria based on their experience and knowledge before reaching a consensus. In addition, the process is a time-consuming activity for professionals to develop danger scales in a group workshop setting, especially for qualitative scales that had to be created from scratch. It is difficult to find times that more than four or five professionals were available at the same time. As a result, most steps of the process involved two separate discussion groups, and the results had to be consolidated after. In one case, a discussion had to be reopened as the two groups had non-compatible decisions. Nonetheless, a consensus was subsequently achieved.

The project's Time duration is another challenge for this type of research. This research took nearly a year including ethics approval, recruiting stakeholders, conducting focus groups, interpreting the results, developing material for the next step, organizing meetings, and repeating these last four steps multiple times. Further, many of the criteria required identifying adequate data, extensive data treatment, in some cases simulations to determine values not available on all streets (such as traffic volumes, truck volumes), and computer programming.

Data availability is another important limitation. As I did not have data for all boroughs in Montreal, some boroughs had to be excluded from our study. In addition, due to the lack of what I termed "ideal data" (what would ideally be used), I sometimes had to use proxies. To improve the accuracy of our tool, was to prepare a list of the criteria with both ideal measurements and possible measurements and on the basis of available data, I started measuring each criteria. One example is a lack of true speed data (ideal) versus using the posted speed limit (proxy). Whenever I could access better data, I updated the criteria measurement and scale. Furthermore, the study does not account for temporal variations in traffic danger, such as differences between weekdays and weekends or seasonal changes that could impact traffic danger.

The proposed model was specifically developed for Montreal. However, it can be exported likely be applied to another city with some adjustments. It is important to note that the criteria selected here are related to traffic danger in this context, which may differ from other cities. Some of the criteria may be the same (for example, factors related to traffic characteristics and traffic calming measures), but group workshops would be needed to set up the scales and scaling constants in order to establish consensus among stakeholders and to determine parameters for assessing traffic danger. An example might be a location with considerable topography variation which could influence traffic danger. Further, data availability differs between contexts and adjustments due those factors would require modifications. However, the process outlined here would be essentially the same.

Conclusion

This study developed a multi-criteria model for evaluating traffic danger on street segments. This study assessed more than 27,000 street segments in selected Montreal boroughs based on traffic danger with special consideration given to children as autonomous users. A key part of our approach was to consider experts', parents', and children's opinions about what creates traffic dangers and incorporate their suggestions perspectives into the model. Based on the MACBETH approach, a constructivist MCDA methodology, the model was built based on stakeholders' preferences, values, and concerns. The model was developed on the experts' experience and group's expertise, knowledge, and goals, criteria and parameters. A number of scales and scaling constants were elicited from the professional experts in order to demonstrate how they interpret the criteria and their relative influence on traffic danger. The study demonstrates the value of an inclusive MCDA-GIS framework for comprehensively evaluating urban traffic danger through stakeholder engagement.

Future research should aim to incorporate real-time data analysis and consider the temporal dimension to provide a more comprehensive understanding of traffic danger. In addition, future research could include developing a tool that could be applied in situations of less data availability, tools that focus on distinct vulnerable populations such as those with disabilities or focusing on specific periods of the day or particular seasons. One application of this tool would be to the creation of a prioritizing tool to determine where safety interventions need to be implemented. To accomplish this goal, a MCDA approach could be used to consider the diverse considerations (traffic danger, exposure, equity, etc.) when deciding the priority of safety interventions. Such a tool would allow for the development of a transparent and consistent means of helping with such important decisions.

CHAPTER 7 ARTICLE 3: A COMPREHENSIVE MULTI-CRITERIA DECISION ANALYSIS (MCDA) TOOL FOR ASSESSING TRAFFIC DANGER AT URBAN INTERSECTIONS

As discussed in the previous chapter and based on the discussions with stakeholders, I identified that the factors influencing traffic danger differ between segments and intersections. Both the type and importance of these factors vary. Building on the previous chapter, this chapter continues to investigate the third objective of this dissertation at the intersection level and explores the practical implementation of this model. The results suggest that a Multi-Criteria Decision Analysis (MCDA) method can be effectively utilized to incorporate stakeholders' insights as crucial inputs in traffic danger assessments. Implementing MCDA allows for the inclusion of the relative importance and, in some instances, the non-linear nature of variables in these assessments. While some studies on traffic danger have employed MCDA methods (Alemdar et al., 2020; Mirmohammadi et al., 2013), these studies often did not directly consider the input of vulnerable stakeholders. Furthermore, they primarily focused on prioritizing a limited number of streets, employing methods that constrained the ability to comprehensively examine a larger network of streets.

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Abstract

Traffic danger is of paramount concern for urban planners and transport authorities as it threatens people and limits their autonomy. Intersections are critical points in urban transport networks where traffic flows converge, giving rise to potential collisions and posing great risks to road users. Ensuring intersection safety is particularly critical in densely populated cities, where vulnerable groups are at heightened risk. Traffic danger at intersections involves a complex interplay of factors. Also, it is evident that these variables do not have an equal or linear impact on traffic danger, requiring a sophisticated approach to assess it. Input from diverse stakeholders, such as urban planners, traffic engineers, community groups, and policymakers, is necessary to get a holistic perspective.

The purpose of this study is to develop a comprehensive tool to assess traffic danger at intersections using a Multi-Criteria Decision Analysis (MCDA) method. The tool aims to provide a rigorous evaluation framework by integrating diverse stakeholder perspectives and developing a transparent and trustworthy assessment tool.

Children as a group are more likely to walk than others to reach their destinations and various characteristics such as height and a lack of experience can put them at greater risk. As such, input from children, parents, and experts were sought to identify key factors of traffic danger. The factors were then systematically analyzed by experts which led to the construction of evaluation criteria, both qualitative and quantitative. Our approach allows for detailed assessments of traffic danger, reflecting the complex interplay between various factors. The model, implemented in a geographic information system, was validated with experts as a final step. It was applied to intersections within the city of Montreal, with special consideration to children as a vulnerable group. The findings highlight critical safety concerns and provide actionable insights for urban planners and policymakers aiming to achieve Vision Zero objectives. It is meant to be used as a decision support system to help implement traffic danger mitigation measures.

Keywords: Traffic danger, Intersection, Built environment, Stakeholders, Criteria, MCDA

Introduction

Intersections pose unique safety challenges due to the convergence of multiple traffic streams, resulting in greater complexity and risk (Bennet & Yiannakoulias, 2015). While segments primarily involve linear traffic movement, intersections present drivers, pedestrians, and cyclists with conflicting decisions within tight spatial and temporal constraints, increasing the likelihood of collisions. Nearly half of all injury-related traffic crashes occur at intersections, highlighting the need for comprehensive tools to assess and prioritize these high-risk areas (Morency et al., 2015a). Data from the Société de l'Assurance Automobile du Québec (SAAQ) shows that there were 392 deaths on Québec roads in 2022, 38 of them related to the city of Montreal (SAAQ, 2023). This value represents an increase of 29.3% for Montreal over the period from 2017 to 2021.

Addressing intersection safety requires a more comprehensive approach than what has been the typical approach. Previous assessments of traffic danger can be classified as traditional (statistical analysis using historical crash data or questionnaires) and observational (driving simulators and videography analysis) (Sheykhfard et al., 2021). These traffic danger assessment methods provide valuable insights but have notable limitations. Using driving simulators, despite their usefulness, lack authenticity and validity as they cannot fully replicate real-world conditions, causing drivers to be less cautious and affecting data reliability (Lakim & Ghani, 2022). They are also costly and can cause simulator sickness due to the mismatch between visual stimuli and physical sensations (Shen et al., 2023). In addition, they fail to capture behavior variations across different road sections, driver perspectives, and detailed behaviors. Traditional methods face issues with data completeness, accuracy, underreporting, and self-reporting biases (Sheykhfard et al., 2021). They often overlook the varying impact of different level of variables (causes) on traffic danger and stakeholders' views, leading to incomplete or biased results.

Various factors influence traffic danger at intersections, including design characteristics (Ni et al., 2016), street attributes leading to the intersection (Bonela & Kadali, 2022), and the type of traffic control implemented (Morency et al., 2015a). These variables have often been analyzed independently, without considering their interactions. Moreover, the relationships between different types and levels of these factors and traffic danger are typically neither equal nor linear. Additionally, these factors do not have equal weight concerning traffic danger. Therefore, there is a need for a tool that considers all these issues in the assessment to provide a comprehensive evaluation of traffic danger at intersections

How traffic danger is understood or assessed can vary between stakeholders such as traffic engineers, urban planners, police officers, children, and their parents. Each group has their specific and sometimes conflicting views on traffic danger. Considering these key opinions could increase the accuracy and acceptability of the assessment as stakeholders are more likely to support and implement traffic safety measures that reflect their concerns and viewpoints. Multi-Criteria Decision Analysis (MCDA) provides a framework that allows for the integration of a variety of factors based on their importance with respect to specific problem. (Donais et al., 2019b). Considering the characteristics of MCDA, it can be an appropriate method to assess traffic danger with input from vulnerable users such as children.

This research fills a critical gap in existing traffic danger assessment methodologies by integrating the perspectives of different stakeholder groups, such as children and their parents, as well as various experts. Their viewpoints on intersection safety, particularly concerning children's routes to their destinations and residential areas, reveal their unique vulnerabilities. A further benefit of this tool is that it explicitly identifies intersections with high risk based on interactions among multiple criteria. It also reveals how different factors contribute to these risks.

To demonstrate the applicability of the MCDA model to urban planning and traffic safety projects, real-world examples are used. As a result, the report makes several actionable recommendations to improve the safety of children at intersections, which will, in turn, enhance the safety of other demographic groups. Intersections that are safe for children are likely to be safe for the majority of road users. Ultimately, this tool provides policymakers with a resource that helps them align with Vision Zero principles to build a safer, more inclusive city.

Background on traffic danger assessment

In traffic danger assessment literature, the term "traffic danger" is often used in a broad sense, primarily referring to crash rate analysis or collision risk (Merlin et al., 2020). This traditional definition of traffic danger is closely related to collision risk, which is based on the combination of crash rates and exposure, typically measured by the number of vehicles or people crossing each intersection (Merlin et al., 2020). For this research, traffic danger refers to the risk of harm or injury that road users, especially vulnerable groups like pedestrians and cyclists, face in traffic environments and which is influenced by different factors such as the built environment, traffic characteristics, and behavior. Various methodologies have been developed to identify, analyze, and mitigate risks associated with road use. For example, Lakim and Ghani (2022) define traffic danger assessment as encompassing a range of methodologies aimed at understanding and reducing the risks inherent in road usage. In another example, traffic danger assessment methodologies categorized into two main groups: passive analysis and active analysis (Sheykhfard et al., 2021). Passive analysis typically involves the examination of historical crash data to identify patterns and trends or surveying communities about perception of traffic danger, thereby informing safety improvements. In contrast, active analysis includes real-time monitoring and proactive measures to prevent collisions before they occur (Sheykhfard et al., 2021). One commonly used method in passive group is identifying crash-prone sites through analysis of crash databases and applying statistical models (Coll et al., 2013). However, this method's accuracy relies on the quality and completeness of crash reports. Inaccuracies or omissions can lead to flawed results (Thakur & Biswas, 2019). For example, hotspot analysis identifies locations with high traffic crash incidences and highlights areas needing intervention (Zahran et al., 2021) and confirmed some unreliable results because of the lack of collision data. Questionnaire data is another approach within this group, involving surveys to gather data on road user attitudes, behaviors, and perceptions related to safety. This data provides insights into factors influencing road user decisions and risky behaviors (Morency et al., 2015a). Using questionnaire, Rankavat and Tiwari (2020) tried to find an interrelationship among pedestrians' risk perception, road crossing preferences and actual crash risk. Although questionnaires are useful for evaluating events such as conflicts and can provide researchers with valuable information on issues that increase the potential for crashes, they often suffer from insufficient data on road conditions or road users. Important information on crash situations is frequently lost due to various factors, such as inaccuracies in reports or incomplete information.

Another recent approaches include simulation studies, conflict analysis and observational studies (Sheykhfard et al., 2021). Driving simulators create virtual environments to study road user behaviors and predict the impact of various conditions (Sobhani et al., 2013; Zhou & Huang, 2013). Zhou and Huang (2013) used simulators to pre-evaluate intersection safety, finding that lower speed limits improved safety. Pedestrian simulators have also been used to study risky behaviors in children (Zafri et al., 2022). Conflict analysis is another approach in traffic danger assessment which studies near-miss incidents as proxies for crashes through videography (Zheng et al., 2021). Fixed-camera videography captures natural road user behaviors and used video-based data to evaluate safety at pedestrian crossings and in mixed traffic flows, respectively (Sheykhfard & Haghighi, 2020). Although these approaches provide the opportunity to examine the interactions of road users with each other, there are several problems with using driving simulators . One major issue is that the real world cannot be fully simulated in every detail. Additionally, these methods tend to be very costly.

The discussed approaches all have their benefits, but none of them are primarily focused on traffic danger assessment, but rather on collision risk assessment. Furthermore, the perspectives of different stakeholders have been largely ignored during the assessment process. Stakeholder engagement incorporates diverse perspectives into traffic danger assessment Multi-criteria decision aiding (MCDA) methods, like the Analytic Hierarchy Process (AHP), TOPSIS, and PROMETHEE, provide structured frameworks for integrating data and objectives in previous literature (Alemdar et al., 2020). AHP, developed by Saaty (1980), uses pairwise comparisons to estimate criteria weights. However, AHP assumes criteria independence, oversimplifying complex decision problems (Munier et al., 2021). Also, it is limited to manageable number of alternatives. TOPSIS ranks alternatives based on their distance from an ideal solution. Mirmohammadi et al. (2013) used TOPSIS to prioritize factors affecting collision rates. However, TOPSIS assumes criteria independence, which may not reflect real-world scenarios with correlated criteria (Macharis & Bernardini, 2015). Another approach in MCDA tools is MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) which is novel in traffic danger assessment. MACBETH creates interval-level scales for criteria, whether qualitative or quantitative, deriving criteria weights and obtaining aggregated scores for alternatives (Bana e Costa & Beinat, 2005). This method helps stakeholders reach consensus and ranks alternatives using M-MACBETH software (Donais et al., 2019b). Though less common in transportation planning, MACBETH could be used to develop a detailed traffic danger assessment.

Although some research has applied Multi-Criteria Decision Analysis (MCDA) to traffic danger, our work advances this field in several significant ways. Previous studies have applied MCDA, but they have certain limitations, as discussed earlier. For instance, earlier research has focused on a limited number of segments (Martins & Garcez, 2021) or specific types of intersections

(Ammanatidou et al.). While these studies are valuable, our work identifies the differences between segments and intersections as a crucial factor. Consequently, we developed models for both segments and intersections.

Additionally, our goal is to achieve a global traffic danger score for all intersections in a city. Traditional MCDA approaches like AHP or TOPSIS are not suitable for this purpose. Therefore, I have explored alternative methods to address this challenge effectively. In this paper, the definition of traffic danger relates to hazards and injuries caused by traffic. Based on this, traffic danger assessment involves considering the causes and various influences of traffic danger and determining their importance. I also aim to incorporate information from all stakeholders to provide a comprehensive and detailed view of the factors influencing traffic danger. Based on that, the model proposed in this paper attempts to address the issue of the previous approach in assessing traffic danger using MACBETH. According to our knowledge, this project is the first application of MACBETH to assess the danger of traffic at intersections.

Methodology

MCDA encourages direct participation from all parties involved in discussions and dialogues, fostering group learning (Banville et al., 1998). This method enhances decision-making by involving individuals with expertise in the problem or those affected by it. These interactions help identify all variables and criteria, which are then weighted and incorporated into the decision problem (e Costa & Oliveira, 2012).-MACBETH is a MCDA method designed to assist decision-makers in quantifying the attractiveness of various options using qualitative judgments about differences in attractiveness (Bana e Costa & Beinat, 2005). This approach employs an iterative questioning procedure that involves pairwise comparisons, during which the decision-maker is asked to provide qualitative preference judgments. MACBETH helps in assessing a large number of intersections, which is a limitation of other MCDA methods, using different criteria and aggregating these criteria based on their importance while considering their interval scales. Figure 7.1 illustrates the conceptual framework of the MCDA approach. The decision-making process within this framework comprises three main phases: structuring, evaluation, and validation and recommendations. Although these phases are distinct, they are interconnected and should be analyzed collectively to avoid any gaps that might impair the final results or improperly influence the decision-making process.

Figure 7.1 MCDA framework

To illustrate the applicability and effectiveness of our Multi-Criteria Decision Analysis (MCDA) tool, we conducted a case study focusing on the city of Montreal. Montreal is a densely populated urban area with a diverse range of intersection types and traffic conditions. As such it provides an ideal setting for evaluating intersection safety.

7.1.1 Structuring phase

The structuring phase defines the decision problem and identifies relevant variables. Focus group discussions were used in this phase as they are an effective qualitative method to gather diverse perspectives, allowing for the emergence of unknown opinions (Adler et al., 2019). Focus groups are valuable for collecting data on the perceptions, attitudes, and beliefs of stakeholders (Adler et al., 2019). They are recognized as an effective tool for participatory research.

Due to geographical constraints, the focus group discussions were held online. The focus groups were led by the first author under the supervision of senior researchers. The focus groups were recorded with consent from the participants. Assistants who were native speakers of either French or English were hired to take notes in case of any technological problems. An online whiteboard with "sticky notes" via MIRO (MIRO, 2023) was used to foster diverse opinions. Each meeting began with a short presentation of the study and its main objectives, followed by a brief explanation of the methodology. Participants were then asked, "What factors can influence traffic danger?" This prompted an exchange of experiences and opinions, forming the basis for sensemaking. Variables were identified through this intense idea exchange. After the focus groups, the recordings were transcribed, and the notes were summarized. A thematic analysis was conducted to finalize the list of criteria. This involved clustering variables based on their relationships. The detailed steps of this process are discussed in chapter 5.

The subsequent steps involved defining measures for each criterion. Initially, measures discussed during the meetings were considered. For example, participants mentioned obstacles such as parked vehicles when discussing the importance of visibility at intersections. Measures not identified in the discussions were derived from the literature. Available data were then searched to find possible measures, and spatial analysis via GIS was used to finalize them. All criteria for this model are qualitative, and some, like intersection design, involve complex spatial analysis and validation for accuracy. Additionally, the segment traffic danger criteria is the result of another MCDA model for calculating the traffic danger index at the street segment level, detailed in another paper. The explanation of criteria, their measurement and levels can be seen in Appendix E. A description of each criterion is given next.

Segment danger index

This criterion defines the level of danger for each segment reaching an intersection. The preference for this criterion was determined based on the results of a previous study our research team conducted at the street segment level based on the MCDA model (see chapter 6). The performance level of this criterion was determined by considering the danger levels of all streets at intersections. Then, discussing in the subgroup workshop, I assigned different combination of danger levels in five different performance levels, starting safe to very dangerous (see Appendix E). The results of this workshop were validated by all experts during a meeting.

Following consideration of possible options in the study area, five levels were constructed for evaluating an intersection on this criterion: 1) Safe 2) Acceptable 3) Somewhat Dangerous 4) Dangerous and 5) Very Dangerous.

Intersection design

The criterion intersection design considers the type of street and the shape of the intersection. It also considers the class of streets at each intersection. Two main types of intersections were considered: three-way and four-way. To classify streets, I used the main classification of streets for the city of Montreal which consists of nine classes. Private streets and highways were removed since they are not accessible to the public or pedestrians in the case of highways. The remaining classes were divided into three groups: local, collector, and arterial. A total of four performance levels have been defined for the study area based on the possible options: safe, acceptable, somewhat dangerous, and dangerous.

Traffic calming

Using this criterion, intersections are classified according to whether traffic calming measures are in place and, if so, what type and how many they contain. An example of traffic calming at intersection is elevated intersection (See Appendix E). A series of categories was defined based on data provided by the City of Montreal: 1) intersections without traffic calming measures 2) intersections with very little traffic calming effect 3) intersections with some traffic calming effect, and 4) intersections with very good traffic calming effects.

Traffic control

The type of traffic control was identified as another criterion. All stakeholders agreed that traffic control plays a significant role in determining the degree of danger at intersections. Our study area contains five different types of traffic control: all ways stop signs, traffic signals with pedestrian signals, traffic signals without pedestrian signals, stop signs in one direction without traffic control in the other direction, and no traffic control at intersections

Intersection visibility

Participants also discussed the importance of pedestrian and child visibility at intersections during their discussion. Drivers can make safer driving decisions when they can clearly see pedestrians, such as yielding the right of way or slowing down. In order to evaluate this criterion, I decided to check whether there is a possibility of parking near the intersection. I used 5-meter buffer zones from the intersections because, according to previous research, parked vehicles significantly obstruct visibility within that distance (Kurek & Macioszek, 2021).

Based on the available data, all options were classified into three categories: low visibility (all lanes allow parking), medium visibility (some, but not all lanes allow parking), and high visibility (no parked cars allowed

Presence of point of interest and commercial area

This criterion represents the impact of land use on traffic danger. The stakeholders discussed how different land uses are not equally important. For instance, the presence of a school has a different impact on traffic danger than the presence of a library. As a result, consideration was given not simply to the number of points of interests present, but also the type. The size of the commercial area was also identified as being an important consideration for traffic danger. The difference between a small local shop with no parking lot does not have the same impact on traffic danger as a larger one with a parking lot (and that a shop with a few parking spaces is not the same as a large retailer with a massive lot). These two factors (points of interest, commercial size) and the resulting combinations evident in the study area resulted in four different performance levels: 1) safe (e.g., residential area with no commercial area) 2) acceptable (presence of community center and small commercial area), 3) somewhat dangerous (presence of transport hub and medium size commercial area), and 4) dangerous (presence of big commercial area).

Bicycle infrastructure design

Bicycle infrastructure is considered for its impact on the street's traffic danger and special consideration is given to its impact on pedestrian safety. The impact of bicycle infrastructure on cyclist safety is not what is being measured here. The different types of bicycle infrastructure can potentially act as traffic calming measures at intersections since, in the case of Montreal, they can narrow the street and increase visibility. The key consideration is the impact of the bicycle infrastructure on the likelihood of death from traffic although collisions involving cyclists and pedestrians can occur, the likelihood of death is lower than if it were a car/SUV/truck etc. Based on this, I defined the performance level based on the impact on traffic danger by the different bicycle infrastructure types. This resulted in defining three levels related to their impact on traffic danger: no effect (no bicycle infrastructure), little effect, and some effect.

7.1.2 Evaluation phase

The evaluation phase began with selecting an appropriate MCDA model based on the criteria. Considering the need for an interval scale and the requirement to weight the criteria relative to each other, I chose MACBETH. This interactive process constructs numerical interval scales to quantify differences in the attractiveness of items (Bana e Costa & Beinat, 2005). Additionally, MACBETH helps derive criteria weights or scaling constants and obtain an aggregated score for each alternative (Donais et al., 2019b).

A subgroup of research team experts identified the direction and reference levels for each criterion. Two reference levels were needed: a lower level, which is neither safe nor dangerous, and a higher level, which marks the starting point of traffic danger concern. Next, using MACBETH, the perceived differences between pairs of performances have been defined. Given that the study area includes over 16,000 intersections and considering all possible criteria options in Montreal, I aggregated these options into fewer groups (see Appendix E). For example, visibility was categorized into three levels: Low, Medium, and High. For visibility, the lower level is high, and the higher level is medium visibility. Table 7.1 illustrates the reference levels for all criteria.

Table 7-1 Criteria reference level

Criteria	Lower level	Upper level
Segment danger level	Acceptable	Somewhat dangerous
Intersection design	Medium	High
Traffic control	All way stop sign	Traffic signal with pedestrian signal
Bike path design	Some effect	Little effect
POI & Commercial area size	Medium	High
Traffic calming	Good effect	Some effect
Intersection visibility	High visibility	Medium visibility

Participants expressed perceived differences in the impacts on traffic danger between each performance level (e.g., for Intersection visibility: Less Visible, Somewhat Visible, and Visible) on a 7-point semantic scale: null, very weak, weak, moderate, strong, very strong, or extreme. Figure 7.2 displays the value judgements from the panel's discussion on intersection visibility as an example. As shown in Figure 7.2, the relative difference on traffic danger between Less Visible and Somewhat Visible was judged to be moderate, whereas the difference between Less Visible and Visible was judged to be very strong. This step was conducted with a smaller group of experts and validated in the main expert workshops. The matrix of value judgments and the scales were obtained using the M-MACBETH software (www.m-macbeth.com/). Appendix F includes the value judgements for all criteria.

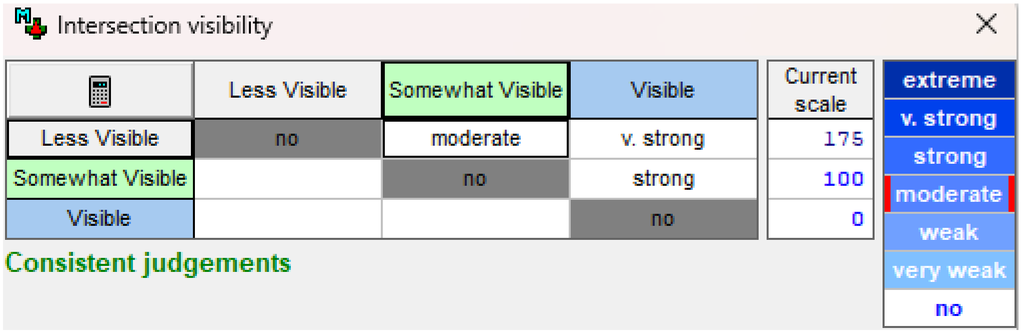

Figure 7.2 Value judgements for the criterion Intersection visibility

Another crucial part of the evaluation phase involved determining the weight of criteria. This required workshops with the traffic danger experts. I created several fictious intersection scenarios, each focusing on one factor at the "higher" level while others were at the "lower" level. This approach, essentially says, "all other criteria are at the lower, non-problematic level, but this one criterion is at the level where traffic danger starts to become a concern." A fictious example was made for each criterion (Table 8-1) where that level was at the upper (becoming a problem) level.

I invited different experts to two meetings to make this process manageable. In these meetings, experts compared pairs of these made-up intersection scenarios. For each pair, they first individually chose which scenario they thought was more dangerous. If differences in opinion existed, the group would debate until a consensus was achieved. Then, each participant used the 7-point semantic scale to rate how much more dangerous it was on a scale from "no difference" to "extremely different." The group would then discuss until a consensus was achieved for the relative importance on traffic danger. This is a challenging mental task. I found that one effective approach was to first present a scenario where an intersection was generally fine (lower level) except for two criteria, which were at a somewhat problematic level (higher level). I then asked participants which of these two criteria they would change to a non-problematic level to reduce traffic danger. This method helped to identify which scenario was perceived as more dangerous.

For example, consider an intersection where has three way (streets) being all collectors, and there is a bike lane (not separated but just marked on the street). Would you change the design of intersection and street type (e.g., changing the streets to local) or changing the bike lane into separated lane? Experts debated and decided that improving intersection design would reduce danger more. The difference between these first scenarios was judged to be moderately to strongly more dangerous than scenario two. Figure 7.3 shows this outcome.

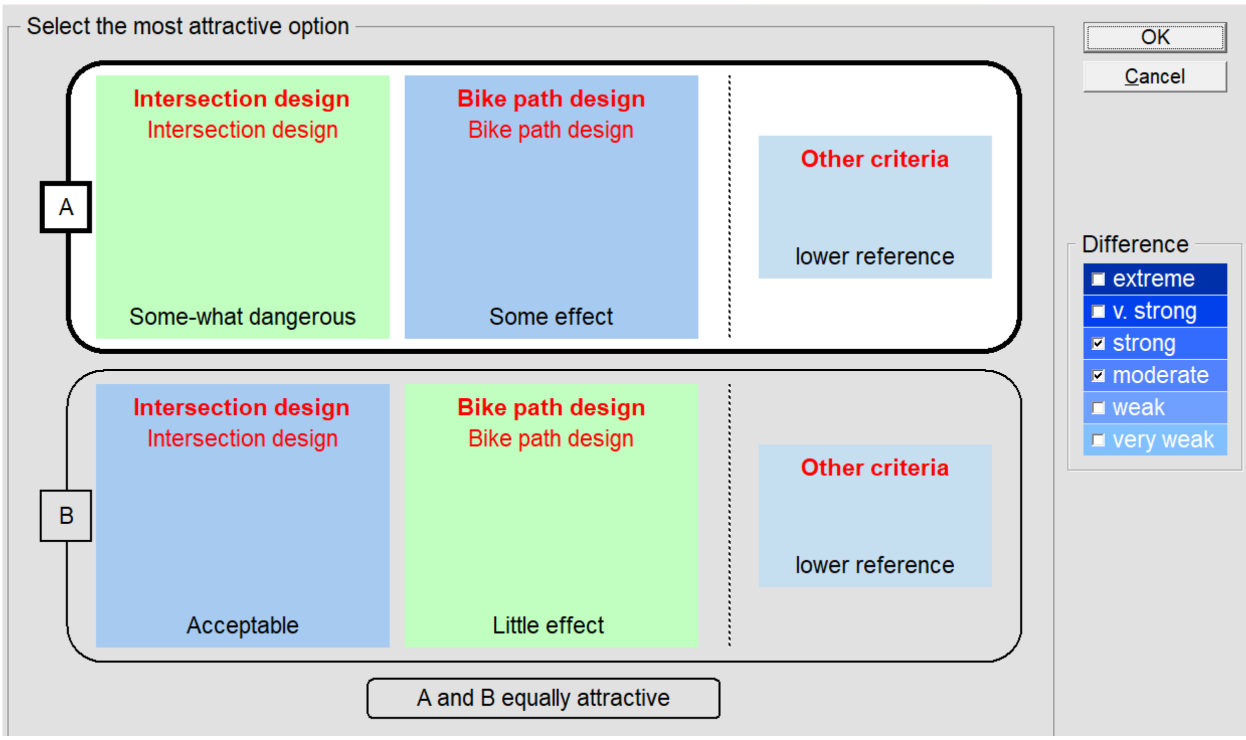

Figure 7.3 Comparison of traffic control and traffic calming criteria

This exercise was repeated for all scenario combinations, and the experts' ratings were used to calculate the weights for each factor.

These evaluations were used to calculate an overall traffic danger score for each intersection using the weighted sum formula in equation 1:

Equation 1

$$S = \sum_{i=1}^{n} w_i x_i$$

where:

S is the weighted sum,

n is the total number of criteria,

w_i is the weight of criterion i,

x_i is the scale associated with criterion i.

By combining MCDA with GIS to process the data, I ranked the danger levels of intersections and created maps to visualize the outputs.

7.1.3 Validation and recommendation phase

Validating the models is essential to ensure that the model's estimates accurately reflect participants' knowledge. Our model was validated by comparing its ranking of 23 intersections with the rankings provided by participants. These intersections involved a wide range of contexts and two fictitious alternatives (all "lower" and all "upper"). Each expert categorizes the examples independently into five levels of danger. Whenever there was disagreement between experts, the opposing viewpoints explained their reasoning until consensus was reached. Following that, the experts' consensus was compared to the model's estimations. After some adjustments, it has been found more than 90% of the experts' rankings correlated with the model results (21 intersections out of 23 intersections).

This phase also involved discussing possible options and changes to increase the model's accuracy. During the validation phase and discussions with the expert group, several recommendations were made to enhance the model's accuracy. In this context, small changes in performance levels were identified for the model to be improved. For example, during the validation meeting and discussion with experts regarding traffic control at intersections, I identified an issue where intersections with stop signs only on the minor road were incorrectly categorized as all-way stop intersections in the model. This misclassification typically led to higher traffic risks on streets without proper control. Consequently, I added one performance level to the traffic control criteria, though the reference level remained unchanged.

Results

Table 7-2 Weighting matrix for the seven criteria used to determine the traffic danger at intersections.

Criteria	segment	Traffic calming	Intersection visibility	Intersection design	Traffic control	POI-Commercial	Bike path design	all lower	Current Scale	Semantic judgement

Table 7.2 Weighting matrix for the seven criteria used to determine the traffic danger at intersections (continued).

[segment]	no							positive	31.34	Extreme
[Traffic calming]	weak-moderate	no						positive	22.39	Very strong
[Int-visibility]	weak-moderate	moderate	no					positive	17.91	Strong
[Intersection design]	moderate	moderate	moderate	no				positive	13.43	Moderate
[Traffic control]	strong	moderate	weak-mod	moderate	no			positive	8.96	Weak
[POI-Commercial]	strong	moderate	moderate	moderate	moderate	no		positive	4.48	Very weak
[Bike path design]	vstrg-extr	weak-mod	moderate	mod-strong	moderate	no	no	positive	1.49	No
[all lower]	positive	positive	positive	positive	positive	positive	positive	no	0	

Due to data limitations in some areas of Montreal, our analysis focused on 13 boroughs, as shown in Figure 7.4. Approximately 16,500 intersections were evaluated using our proposed model.

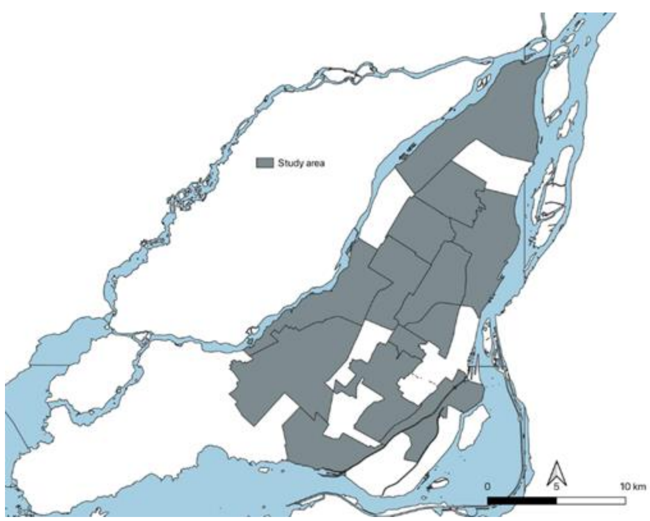

Figure 7.4 Study area of the island of Montreal.

The results are presented at two levels: initially, intersection maps for each of the seven criteria are shown in Figure 7.5. These maps use a color gradient to represent danger levels ranging from safe to very dangerous. It is evident from these criteria maps that performance values can vary significantly from one intersection to another.

Figure 7.5 Criteria interval scales on the island of Montreal

Figure 7.5 Criteria interval scales on the island of Montreal (continued)

Figure 7.5 Criteria interval scales on the island of Montreal (continued)

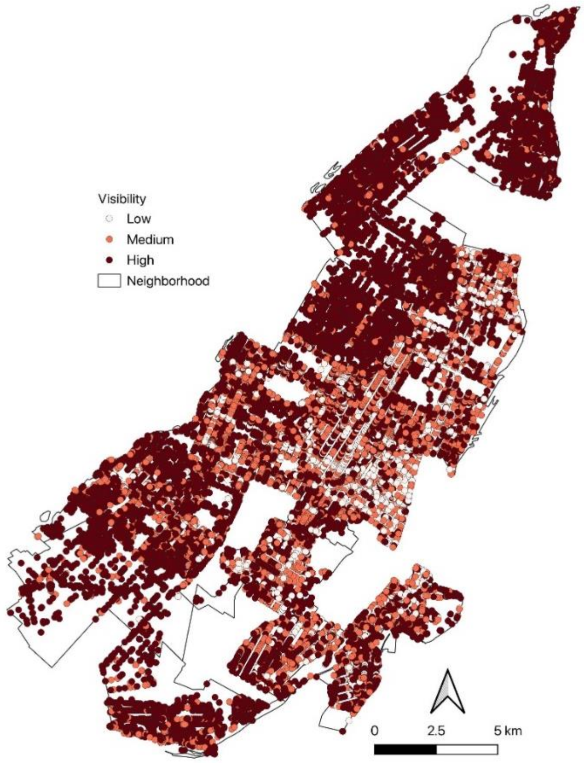

Figure 7.6 Criteria interval scales on the island of Montreal.

For the aggregated results across the entire study area, the overall traffic danger was classified using the Natural Breaks method in GIS. This method ensures minimal variance within each class and maximizes variance between classes, highlighting the differences in danger levels. This classification distinctly delineates the traffic danger levels into five classes. Examining example intersections for each class they were then termed: Safe, Acceptable, Somewhat dangerous, Dangerous, and Very dangerous. However, since the natural breaks did not always align with the descriptive labels assigned to each group, the traffic danger score ranges were adjusted following a validation process with the experts. The final classifications are presented in Figure 7.6. During the workshop, we evaluated the traffic danger scores for each group, and after thorough discussion and reaching a consensus with the experts, adjustments were made to the score ranges, particularly for the 'safe' and 'very dangerous' categories, to better reflect the group's assessments.

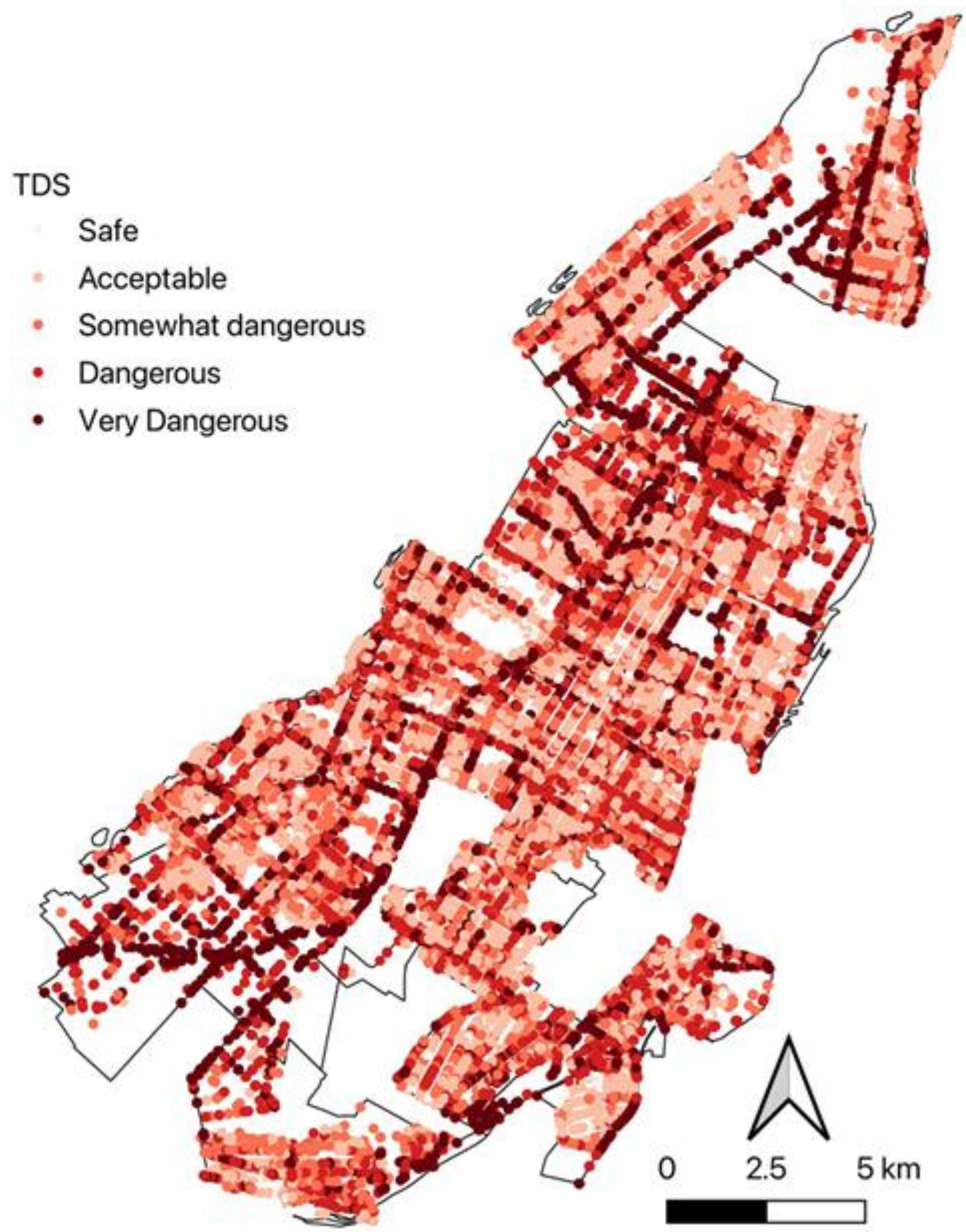

Figure 7.7 Traffic Danger classifications of intersections in Montreal.

A higher proportion of intersections fall into the dangerous and very dangerous categories near arterial roads. As shown in Figure 7.8, the most common classification is Acceptable, whereas very dangerous intersections are the least frequent.

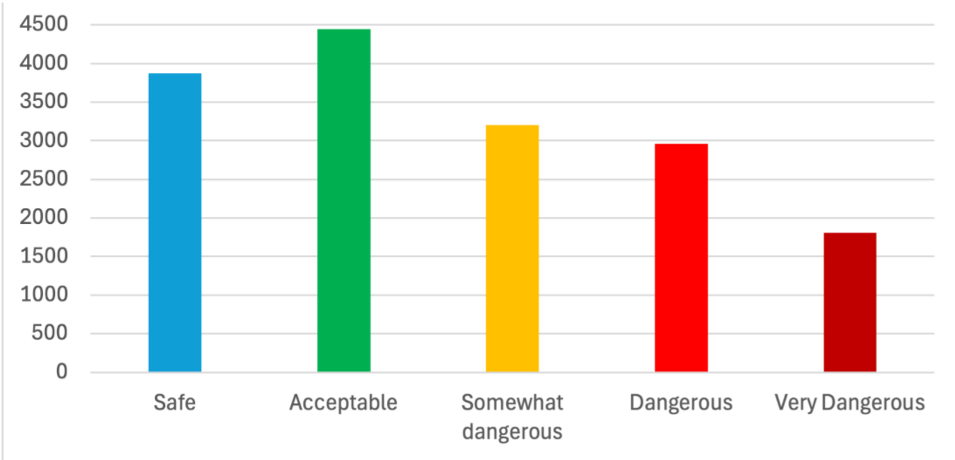

Figure 7.8 Frequency of traffic danger classification of intersections in Montreal.

Analyzing the results at the neighborhood scale allows us to determine which areas are more sensitive to traffic danger at the intersection level. Figure 7.9 illustrate the distribution of different danger classes across the boroughs.

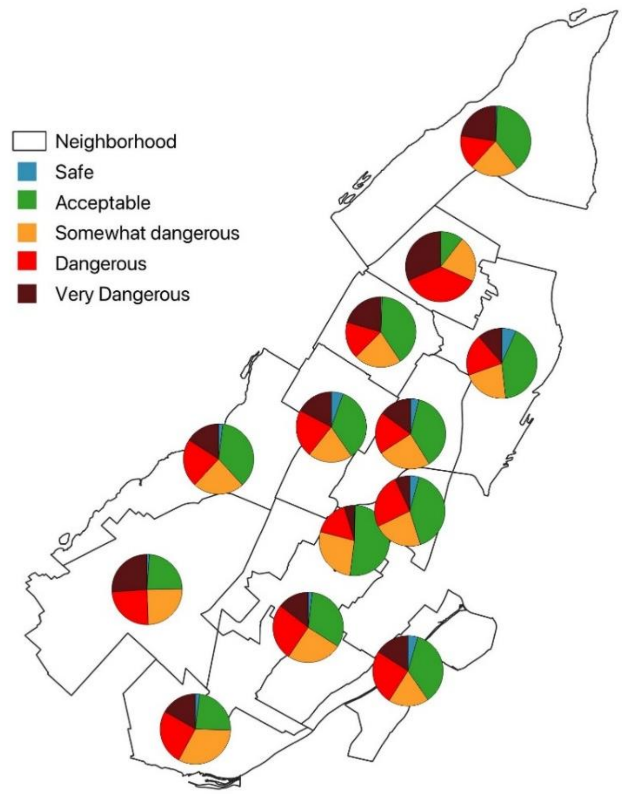

Figure 7.9 Proportion of traffic danger class in different neighborhood

Discussion

This project represents a novel application of Multi-Criteria Decision Analysis (MCDA) to assess traffic danger at the intersection level. By utilizing the MACBETH approach, I integrated both the elements often overlooked in traditional assessments, providing crucial insights for policy formulation. The analysis is designed to assist decision-makers, but also the public, to have a transparent tool that is validated and that considers a vast number of intersections. The information could be used to help with decisions on where interventions might be needed, but other decision criteria such as exposure would need to be considered.

Our approach pioneered the use of spatial MCDA for assessing traffic danger at intersections across a city. MCDA is characterized by its ability to engage participants in a shared learning process. As meetings progressed, stakeholders developed a unified understanding of the project's objectives and the multicriteria methods used. Consistent with findings from other studies

(Donais et al., 2019a; Donais et al., 2019b), this learning process enabled stakeholders to refine or revise their opinions. The deliberative aspect of the multicriteria process enhanced their understanding of the decision problem and outcomes, facilitating more effective communication (Macharis & Bernardini, 2015). Additionally, the use of MACBETH allowed for a comprehensive analysis of various aspects of the problem (Bana e Costa & Beinat, 2005). This included uncertainty, imprecision, interactions among criteria, and the selection of appropriate measurement scales.

This project's results are grounded in the understanding of traffic danger of diverse stakeholder groups including children. Their inclusion provided valuable insights into the unique vulnerabilities and experiences of younger road users, which helped ensure that the assessment captured a more comprehensive picture of traffic danger. Involving children and other stakeholders also contributed to more targeted and effective safety measures, making the results more relevant and actionable . This highlights the importance of diverse stakeholder involvement. Children possess unique characteristics that increase their vulnerability to traffic danger, which is frequently cited as a reason to restrict their freedom to travel. Therefore, it is crucial to consider their perspectives. Future research could apply this approach to other vulnerable groups, such as the elderly and individuals with disabilities. In Montreal, the quantified measures of traffic danger could aid policymakers in prioritizing interventions at intersections. These interventions range from minor adjustments to complete redesigns based on the severity of the assessed danger and the potential for mitigating negative impacts.

While our model introduces innovative criteria, it also aligns with established factors identified in the literature, such as visibility, traffic control, and calming measures (Bennet & Yiannakoulias, 2015; Harwood et al., 2003; Miranda-Moreno, Morency, El-Geneidy, et al., 2011; Rankavat & Tiwari, 2016). These similarities confirm a broad consensus on several aspects of traffic danger, reinforcing the model’s relevance to current professional practices. These studies highlighted the importance of various factors, but they did not consider the significance of different types and levels of these criteria. For example, they did not explore the differences between various types of traffic control or traffic calming measures in relation to traffic danger. Previous studies often focused on identifying the relationship between these various variables and collision rates, rather than examining the broader concept of traffic danger. Our novelty in this research is the comprehensive and detailed consideration of these factors by examining different types and levels of them.

However, the project also faced limitations. Organizing focus groups with children is more difficult than with adults because of the more stringent ethics requirement and the need to first get the permission of parents. As the meetings were online and there was a compensation offered, I found that some adults were trying to participate in place of children. Such barriers might deter practitioners and researchers from seeking children's input, potentially ignoring their valid concerns and perspectives. Initiatives such as Municipal children's councils (e.g., Québec City's Conceil municipal des enfants) is potentially one method to help overcome such barriers to including vulnerable parts of the population. The initial involvement of experts unfamiliar with the MCDA process presented additional challenges, particularly in weighting criteria. This sometimes led to fatigue and potential bias. For example, since the participants were unfamiliar with the process, it was initially challenging for them to compare scenarios for weighting the criteria. Sometimes, the research team needed to remind them to consider all criteria for each scenario. To mitigate these issues, I conducted weighting in smaller groups and validated interval scales in subgroup meetings before broader expert review.

Data availability posed significant challenges, necessitating the removal of some neighborhoods from the study. I prepared two types of data lists for each criterion: ideal data for the most accurate measurements (e.g., street width) and optional proxy measures (e.g., street classification) that could be used when ideal data were not available. This dual approach allowed for continual refinement of criteria measurements as more accurate data became available. This ensured that our evaluations remained as precise and relevant as possible under varying data conditions.

The proposed model is adaptable to various contexts, though it may require adjustments to criteria or performance levels based on local conditions. The tool would require greater adjustments if applied outside of North America where other intersection control devices are more popular such as round-abouts. The approach would be appropriate anywhere, however. Assessing intersections based on their traffic danger levels helps identify areas needing urgent interventions, particularly for vulnerable groups like children and pedestrians. Prioritizing interventions at intersections would require considering additional factors such as pedestrian exposure, sociodemographic variables, and infrastructure quality. The process involves a comprehensive multicriteria approach, engaging stakeholders in defining criteria, evaluating them, and selecting appropriate MCDA methods, such as the potential use of outranking methods.

Conclusion

This chapter presents a comprehensive Multi-Criteria Decision Analysis (MCDA) tool for assessing traffic danger at urban intersections, with a special focus on children's unique vulnerabilities. By integrating diverse stakeholders' perspectives and accounting for the complex, nonlinear relationships among various factors, this tool offers a robust framework for evaluating intersection safety. To address different urban levels of safety concerns, two different street segment and intersection models were developed and implemented.

Based on the MCDA model application in Montreal, urban planners and policymakers can gain insight into critical safety issues. With this tool, intersections that have considerable traffic danger can be identified and the contributing factors understood as the criteria scales are available. This information would permit interventions to address those criteria that contribute the most. The focus on traffic danger is relevant to approaches such as Vision Zero that differentiate between the severity of collision outcomes. The inclusion of children's perspectives ensures that the needs of vulnerable groups are not only considered but prioritized, fostering the creation of safer, more inclusive urban environments.

Overall, this research contributes significantly to the field of traffic safety by introducing a novel, participatory tool that enhances the accuracy and acceptability of traffic danger assessments. The application of the MACBETH method within a geographic information system (GIS) framework demonstrates the potential of combining advanced analytical techniques with real-world data to inform effective policy and urban planning decisions. This tool serves as a decision support system that guides the implementation of targeted traffic danger mitigation measures. This contributes to safer streets for all road users.

CHAPTER 8 GENERAL DISCUSSION

The objective of this chapter is to provide a comprehensive discussion of the research conducted in this Ph.D. project. First, this chapter outlines the overall objectives of the project and how these objectives have been addressed throughout this research. Next, it summarizes the research gaps identified in previous chapters and explains how this study contributes to filling those gaps. The chapter then highlights the advancements made by this research in relation to the existing body of knowledge, illustrating what was known before and what new insights have been gained. Finally, the chapter concludes with a discussion of the dissertation's limitations and suggestions for future research direction.

Addressing Research Gaps Through Targeted Contributions

Transport influences children's health and well-being primarily through traffic externalities and travel behavior. Based on that, the first objective of this dissertation was to provide a comprehensive analysis of the relationship between the built environment, transport, and children's health. This included examining the interactions among various variables and externalities simultaneously, highlighting the multiple ways in which the built environment and transport infrastructure can influence children's health. The existing literature revealed significant gaps in understanding the relationship between the built environment and children's health and well-being, particularly regarding mental and social health impacts. While there was evidence that walkable neighborhoods and land-use diversity positively affect physical activity, the effects on children's mental and social health remain underexplored. Current research focused primarily on physical activity, leaving the relationships between the built environment, social activity, and health unclear. Additionally, inadequate urban design, high traffic volumes, excessive speeds, and a lack of safe crossing points contributed to pedestrian and cyclist collisions, posing physical risks and psychological stress. There was also a challenge in integrating the various components of the built environment into a cohesive understanding of their impact on children's health, given the complexity and variety of influencing factors.

This research made a significant contribution by addressing these gaps and providing a comprehensive analysis of the relationship between the built environment, transport, and children's health. It explored how the built environment influences children's physical, mental, and social health by considering factors such as emissions, noise, traffic danger, transport infrastructure, and land use as independent variables. A holistic and interdisciplinary approach synthesized findings from numerous studies, offering a clearer picture of the built environment's impact on children's health.

The research also proposed a conceptual framework linking the built environment to health outcomes through transport and general health behaviors. This framework guided future research and informed policy-making efforts to create supportive environments for children. Some concepts discussed included enhancing walkability, reducing traffic-related pollution, and providing access to green spaces, offering actionable insights for urban planners and policymakers to create healthier environments for children. However, as the research progressed, it became clear, traffic danger was particularly complex due to the various factors contributing to it. Additionally, traffic danger directly impacts children's active mobility and accessibility, which, in turn, affects their independence in transport. As a result, measuring traffic danger can help identify streets and intersections that act as barriers to children's mobility, enabling more accurately targeted interventions to improve children's health and well-being.

Focusing on traffic danger, a comprehensive definition of traffic danger that specifically addresses the unique vulnerabilities and experiences of children was lacking. Firstly, there was a significant gap in the definition of traffic danger. A lot of previous literature has conflated traffic danger with collision rates and crash risk, but these terms have different definitions and calculations (see chapter 2). To address this issue, this research aimed to establish a comprehensive measure of traffic danger. Before starting the traffic danger analysis process, workshop participants, including both technical experts and general stakeholders (parents and children), were consulted to provide their perspectives on traffic danger. This approach ensured that the definition incorporated both expert technical terms and the broader views of parents and children. This resulted in a more inclusive and accurate understanding of traffic danger.

Previous research has predominantly focused on either objective safety outcomes (such as collisions and injuries) or subjective perceptions of danger by parents and children, without integrating these aspects into a cohesive definition. Furthermore, both objective and subjective measures of traffic danger identified as independent variables that influence traffic danger. Interactions among these factors and their relative importance must be understood, as they interact and influence each other with respect to traffic danger. It is also crucial to incorporate people's perspectives, as conflicts between perceptions and objective measures often arise. For example, data might show that collisions are more frequent at intersections with crossing guards, leading some people to the conclusion that crossing guards create dangerous conditions. However, parents might perceive these intersections as safer due to the presence of crossing guards. The crossing guard might actually reduce danger, but they are put in place at more dangerous intersections so a statistical analysis would identify them as positively correlated with more collisions. This is an example of how the approach applied here could potentially build a more accurate reflection of the impact of features on traffic danger. Moreover, different groups can highlight factors that may be overlooked by the literature. People's ideas and experiences about traffic danger have the potential to add new perspectives to traffic danger assessment. This discrepancy highlights the importance of considering both objective data and community insights to ensure interventions are both effective and aligned with public perceptions.

Children and their parents have often been overlooked in favor of expert opinions, leading to a gap in understanding their lived experiences and perceived risks. Effective traffic danger assessment requires input from different groups of experts such as traffic engineers, urban planners, police officers, as well as children, and their parents as their experience of traffic conditions will not necessarily be the same. However, existing approaches frequently fail to integrate these diverse perspectives, resulting in assessments that may not fully reflect the concerns and needs of all affected parties. To address this, structured focus group discussions with traffic safety experts, parents, and children were conducted. By incorporating these diverse perspectives, this research captured a more comprehensive understanding of the factors contributing to traffic danger. The thematic analysis identified key themes influencing traffic danger for children. Incorporating and comparing the perspectives of children, parents, and experts allows for a holistic view of traffic danger. This comprehensive approach ensures that solutions are informed by the lived experiences of those most affected by traffic danger, increasing the acceptability of future results.

Most existing traffic danger assessments do not sufficiently consider the unique risks faced by children. Children are particularly vulnerable due to their physical and cognitive limitations, yet their specific needs are often overlooked in safety evaluations (Cloutier et al., 2021). This gap results in safety measures that may not effectively protect this vulnerable group, highlighting the necessity for assessment tools that prioritize children's safety and incorporate their specific vulnerabilities. This research emphasized the importance of focusing on children as vulnerable road users with distinct needs by considering factors such as their judgement for speed and distance, their smaller stature which affects visibility, and their higher likelihood of being present in specific land uses such as schools and parks. By prioritizing children's safety, the results can support planning that aims to protect vulnerable populations.

Previous literature on traffic danger has been limited by its tendency to consider only the direct relationships between individual factors and traffic danger, without accounting for the complex interactions among these factors. For instance, the relationship between traffic speed and volume or the combined effect of road design and visibility has often been examined in isolation. This approach overlooks the multifaceted nature of traffic danger, leading to incomplete or inaccurate assessments. This thesis addressed this gap by applying a thematic analysis to uncover key factors, and developing a comprehensive framework tailored to assessing traffic danger specifically for children. The approach helped the understanding of traffic danger criteria and provided actionable insights for improving urban road safety, particularly for young road users. Each theme, derived through thematic analysis of focus group discussions considering interaction among different factors. During the focus groups with various stakeholder groups, we discussed and identified the interactions among different factors contributing to traffic danger. After listing all the relevant factors, we asked the participants how each specific factor influenced traffic danger. When participants responded with "it depends," we recognized that there might be interactions at play. We then continued the discussion to identify the other factors involved in these interactions. (For more details, see the description of criteria in Appendices B and E). It offered a detailed understanding of how these factors contribute to traffic danger. By highlighting these themes, the framework provides a structured method to analyze and address traffic safety issues specific to children.

Current traffic danger assessment methods, have notable limitations. Traditional methods, such as analyzing historical crash data, often suffer from issues like data completeness, accuracy, and underreporting biases. These methods tend to overlook the varying and in some cases non-linear impacts of different traffic danger measures and stakeholder views, resulting in incomplete or biased results. In addition, simulation analyses provide valuable insights but face limitations in accurately replicating real-world conditions. These methods can be costly and may cause simulator sickness, reducing their practicality for extensive use. Furthermore, videography analysis often fails to capture behavior variations across different road sections and detailed behaviors of road users, limiting their effectiveness in comprehensive traffic danger assessments.

The application of Multi-Criteria Decision Analysis (MCDA) methods offers a promising solution to these gaps. MCDA allows for the integration of various factors and stakeholder perspectives, providing a more holistic and accurate assessment of traffic danger. However, the use of MCDA in traffic danger assessment is still in its nascent stages and requires further development and validation. In addition, not all MCDA methods are appropriate for traffic danger. Previous approaches such as AHP have shortcomings, such as neglecting the possibility of non-linear relationships between different variables and their limitation in assessment of high number of alternatives (see chapter 2). Therefore, it is crucial to choose appropriate methods to design a more accurate tool for traffic danger assessment. Considering the complexity of traffic danger assessment in the urban area level, MACBETH method was chosen. Employing the MACBETH method and Geographic Information Systems (GIS), I evaluated traffic danger at a granular street-segment level. This comprehensive approach took into consideration a number of quantitative and qualitative criteria that had been constructed considering the relationships among different variables. This allows for a more accurate and nuanced assessment of traffic danger.

Previous studies usually used simple and straightforward measures for different variables for traffic danger assessment. For example, when considering the importance of land use in traffic danger, they utilized the presence of specific land use such as a school or park as a measure. In reality, all different types of land use need to be considered since they may have different influences on traffic danger. Some land uses need to be considered in depth using their physical features (e.g., area) because their physical aspects also affect their relationship with traffic danger. In some cases, different data and built environment features must be combined to measure one criterion. For example, measuring intersection design not only relates to the shape of the intersection but also to the types of streets reaching the intersection when considering traffic danger. Moreover, when aggregating different factors to assess traffic danger, previous studies often used equal weights for all factors, which does not accurately reflect reality. Some factors may have more severe implications for traffic danger than others, and these differences should be scientifically defined by comparing various situations. In our approach, I addressed this by defining the importance of each criterion through comparisons of different fictitious scenarios and collaborating with experts from diverse fields. This method ensures a more accurate and realistic assessment of traffic danger

Previous literature has mainly focused on specific aspects of traffic danger, such as ranking different types of traffic control, or it has been limited to a small number of streets or intersections. This research addressed these limitations by applying the MCDA model to over 25,000 street segments and 16000 intersections in selected neighborhoods of Montreal, providing a detailed spatial analysis of traffic danger. This approach demonstrated the model's utility in identifying high-risk areas and informing targeted safety improvements. Integration with GIS allowed for the creation of visual traffic danger maps, making results accessible and interpretable for decision-makers and the public. This visual representation facilitated better communication of the findings and supported data-driven policy decisions.

Finally, the factors that influence traffic danger can vary between different locations, such as midblock and intersections. Previous literature has confirmed that traffic danger levels may differ between intersections and street segments, and in some cases, different variables are used for traffic danger assessments in these locations. One of our contributions, stemming from discussions with experts, is the development of two distinct models for intersections and street segments. I conducted separate workshops with experts to develop these models, resulting in some differences in criteria. For criteria that remained the same, their weights differed between intersections and segments. For example, while traffic calming measures are a common criterion, their importance is greater at intersections than at midblock.

Limitations

As can be expected, this study had its limitations. In the first analysis of this dissertation presented in chapter 4, The new framework in considering the relationship between built environment and children health has been developed. The review primarily focuses on the built environment's impact on children's health through transport pathways, with less emphasis on mental and social health connections, which are less developed. Most studies reviewed are from high-income, English-speaking countries, limiting the generalizability of findings. Definitions of "child" vary across studies, affecting consistency and comparability. The paper does not account for longitudinal changes in the built environment's impact on health, and inconsistencies in measurement and reporting make drawing definitive conclusions challenging. Many relationships discussed are correlational, lacking strong causal evidence, particularly for mental and social health outcomes.

Previous research has primarily focused negative externalities such as traffic danger, air pollution, and noise, while positive aspects like physical activity and social interactions are not as thoroughly explored. Although the links with such outcomes are often investigated, there are limited intervention studies examining changes to the built environment and their direct impact on children's health, highlighting a need for more research. The integration of findings from different disciplines is limited, potentially hindering a comprehensive understanding. Lastly, I tried to outline potential interventions but does not deeply explore the feasibility, implementation, and policy implications of these recommendations.

In Chapter 5, I illustrated the use of focus groups with different stakeholders to define traffic danger and identify factors that can influence its level. During this study, I encountered several limitations. Firstly, securing reliable participants for the parents' and children's groups posed a challenge, as some participants showed interest primarily due to the incentive rather than genuine engagement confirming the participation of actual children in one focus group was difficult, resulting in its cancellation. Additionally, scheduling conflicts prevented key experts, such as police officers and policymakers, from participating, which may have affected the comprehensiveness of the study's outcomes.

Moreover, while the study directly involved children and parents, only one focus group was conducted with children, primarily based in Montreal. This raises questions about the generalizability of the results to other contexts, such as smaller urban centers or different driving cultures. The random selection of participants and the mixed-gender composition of the groups might have influenced the dynamics and responses within the focus groups. As well, people's experience is limited to their lived experience, which is likely to be the same country, if not the same city. As such, the ability to know how truly different conditions or street designs might impact traffic danger is limited.

Another limitation is the absence of using new technology in the focus group process, especially with children. Interactive applications and simulations could offer children engaging ways to share their idea about traffic danger. Using advanced simulations in focus groups could provide deeper insights into how children and parents perceive and respond to various traffic situations.

This study relies on data from public sources and surveys. These data may not fully capture essential street design details, such as lane width and traffic characteristics like practiced speed and the number of large personal vehicles. Additionally, due to data limitations, some Montreal boroughs were excluded from the study. In addition, recruiting reliable participants, especially parents and children, for the focus groups was challenging. Initial attempts through online advertising were not always successful, leading to the need for more targeted recruitment methods. All participants were first-time attendees to multi-criteria workshops, requiring extensive time and consideration at various steps. Determining the weight of each criterion was particularly challenging due to the differing expertise and perspectives of the participants. This necessitated lengthy discussions to reach consensus.

The focus group workshops were time-consuming, taking nearly a year to complete. It involved multiple steps, including ethics approval, recruiting stakeholders, conducting focus groups, interpreting results, developing materials, organizing meetings, and extensive data treatment.

The study does not account for temporal variations in traffic danger, such as differences between weekdays and weekends or seasonal changes. Incorporating real-time data analysis and considering the temporal dimension would provide a more comprehensive understanding of traffic danger. Moreover, the study focused on children as a vulnerable group but did not account for other populations requiring additional consideration, such as the elderly or people with disabilities.

CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

This chapter presents the conclusions of this Ph.D. project and offers recommendations for future research. It begins with the presentation of the conclusions, followed by several suggestions for future studies. The chapter concludes with a summary of the entire Ph.D. project.

Conclusions

This Ph.D. project aimed to develop tools that can help planners better understand the impacts of transport on children. Within this broad aim, I identified traffic danger as a critical problem due to its direct impact on children's safety, mobility, and overall well-being. Through our examination of this issue, I recognized several shortcomings in the current approaches to assessing traffic danger, such as the lack of comprehensive consideration of various factors and the discrepancy between objective measures and public perceptions. To address these limitations, I identified Multi-Criteria Decision Analysis (MCDA) as a potential method. MCDA allows for a more nuanced evaluation by integrating multiple factors and perspectives, thereby providing a more holistic and accurate assessment of traffic danger.

A new approach using the MACBETH method integrated various stakeholder perspectives to assess traffic danger. It employed GIS-MCDA techniques to spatially analyze and visualize traffic danger at intersections and street segments, and considered the interconnections between the built environment, transportation, and children's health. These developments contribute significantly to improving future analyses of urban traffic danger and children's mobility.

The key contributions of this Ph.D. research enhanced understanding of three critical urban safety questions: proposing an integrated framework to understand how the built environment and transport affect children's health and wellbeing, building upon and advancing previous reviews; developing more holistic tools to measure traffic danger (as opposed to collision probability) that can be applied to thousands of streets and intersections.

The MACBETH method effectively integrated diverse stakeholder perspectives, enabling a comprehensive assessment of traffic danger. The research highlighted the importance of considering the interactions between different variables, noting that not all relationships with traffic danger are linear; some are complex and non-linear. This insight is crucial for enhancing urban safety, especially for children. Additionally, the application of GIS-MCDA techniques provided detailed visualizations of traffic danger and helped to present results in an accurate and interactive manner.

A new GIS-based tool was developed to present the traffic danger index. This tool allows users to filter and view various layers, display aggregated data by neighborhood, and visualize traffic danger details by clicking on intersections and segments. It demonstrated strong potential for user engagement and effectively conveying complex spatial data.

The research better integrated the various ways that different built environment characteristics might influence traffic danger. Factors such the street segment level, the type of traffic control, and traffic calming measures are some variables related to built environment. Ensuring child safety equates to enhancing safety for the general public.

The advancements in feature integration, stakeholder engagement, and interactive visualization developed in this Ph.D. project will enhance future traffic safety assessments and support the creation of safer urban environments for all road users, particularly vulnerable groups like children.

Recommendations for future studies

The traffic danger assessment tool was applied and validated to the road network in the City of Montreal. To understand the generalizability and limitations of the tool, it is recommended to apply the tool and method in different urban contexts. This research is essential to assess the tools applicability and effectiveness in cities with varying traffic danger related conditions, whether that be infrastructure, traffic characteristics, demographics or considerations that were not pertinent in this context. Different contexts may have different factors to consider, which need to be considered in collaboration with their stakeholders, but the approach and framework can remain the same.

The current study successfully integrated stakeholder perspectives in the traffic danger assessment. Future research should incorporate broader stakeholder engagement, including more diverse groups such as local residents, cyclists, police officers, and others to gain a broader view of traffic danger assessment. This broader engagement will ensure a more comprehensive understanding of traffic danger from multiple viewpoints.

In future studies, exploring face-to-face interviews with children could offer an interactive and engaging environment. Additionally, incorporating serious games could be a valuable tool for engaging young participants. Serious games would allow children to actively participate in simulated traffic scenarios, making it easier for them to express their perceptions of traffic danger in a more playful and natural manner. This approach could enhance data richness and lead to deeper insights into traffic safety from a child's perspective.

Focusing more on vulnerable populations such as elderly pedestrians and cyclists in future studies is crucial. Tailored safety measures and traffic danger assessments should be developed to address the unique challenges faced by these groups. Conducting longitudinal studies to observe the impact of implemented safety measures based on the traffic danger index over time will provide insights into the long-term effectiveness of various interventions and help refine the assessment models.

To improve the accuracy and relevance of the traffic danger index, it is also recommended to incorporate real-time data sources such as live traffic feeds and weather conditions. This dynamic approach will provide up-to-date insights and help in the timely implementation of safety measures. Additionally, integrating the developed interactive platform, such as Mapbox, a web-based mapping tool that allows to create and customize interactive maps, with existing urban planning tools and Geographic Information Systems (GIS) used by city planners is recommended. This integration will facilitate the seamless use of the traffic danger index in urban development projects and policy-making processes.

In this tool, we used the insights from participants in the focus group discussions to identify the interactions among different variables influencing traffic danger. One method would be through integrating MYRIAD, a method designed to address complex decision problems by considering the interactions between multiple variables. The combination with MACBETH could significantly enhance the evaluation process. By integrating MYRIAD into the MACBETH framework, we could account for both the qualitative evaluation of factors and the dynamic interactions between variables. MYRIAD's ability to account for these interdependencies ensures that the model reflects real-world dynamics more accurately.

As part of future research, we plan to expand the validation process of the MCDA tool. While the initial validation was carried out through expert workshops using randomly selected street segments and intersections (as detailed in Chapters 6 and 7), a more comprehensive approach will involve a second round of validation. This will include distributing interactive maps to experts, enabling them to assess a broader range of streets and intersections. Additionally, on-site visits and random observations will be conducted to ensure the accuracy of both the data and the tool within the specific context of the study area. This extended validation will provide deeper insights and further enhance the robustness of the tool.

Investigating the impact and interaction of environmental factors such as air quality, noise pollution, and urban heat islands with traffic danger is another critical area for future research. Understanding these interactions can lead to more holistic strategies that address multiple dimensions of urban health and well-being.

In addition, prioritizing street segments and intersections with respect to traffic danger requires more investigation into different factors and related variables. Examples of these variables include exposure (number of pedestrians crossing each street or intersection), sociodemographic variables, and the quality of available infrastructure. It is crucial to explore these variables in collaboration with different groups of stakeholders to structure the problem and aggregate different variables based on their interactions and importance to have an accurate prioritization index. Based on that, future research can develop another MCDA tool to prioritize them accurately to find the most sensitive places for intervention.

Finally, not all interventions are appropriate for different sensitive intersections and streets. Various factors influence the choice of intervention. Discussing these factors with stakeholders and aggregating and ranking different intervention scenarios using different MCDA techniques need to be done to be effective and acceptable for all groups.

By addressing these recommendations and exploring the suggested future research directions, the comprehensive assessment and mitigation of traffic danger can be significantly enhanced, leading to safer and more sustainable urban environments.

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Ziakopoulos, A., Yannis, G. J. A. A., & Prevention. (2020). A review of spatial approaches in road safety. *135*, 105323.

Zoom. (2024).

APPENDIX A SEARCH TERMS

The following search logic was used to identify literature. It was last conducted in January 2023 using Web of Science (Core Collection).

("built environment" OR "physical environment" OR "urban environment") AND ("children" OR "youth" OR "adolescents") AND ("mental health" OR "psychological well-being" OR "emotional well-being" OR "behavioral problems").

("built environment" OR "physical environment" OR "urban environment") AND ("transport" OR "transportation" OR "active transportation" OR "walking" OR "cycling" OR "public transportation") AND ("children" OR "child" OR "adolescent" OR "youth") AND ("physical health" OR "childhood obesity" OR "physical activity" OR "outdoor play”).

("built environment" OR "physical environment" OR "urban environment") AND ("transport" OR "transportation" OR "active transportation" OR "walking" OR "cycling" OR "public transportation") AND ("children" OR "child" OR "adolescent" OR "youth") AND ("social health" OR "social well-being" OR "social interactions" OR "community engagement" OR "neighborhood cohesion”).

Following comments from reviewers, “nature” was added to the built environment synonyms for each search and two additional relevant reviews on nature and green space were identified. That search was run on the 12th of June 2023.

APPENDIX B SEGMENT CRITERIA DESCRIPTION

Traffic characteristics

This criteria is a combination of speed, traffic volume, number of street lanes and street direction.

Measurement:

Speed: speed limit (km/h)

Traffic volume: Average Annual Daily Traffic (AADT)

Low <2000, 2 Vehicle/Minutes

Medium 2000-3000, 2-3 Veh/min

High>3000

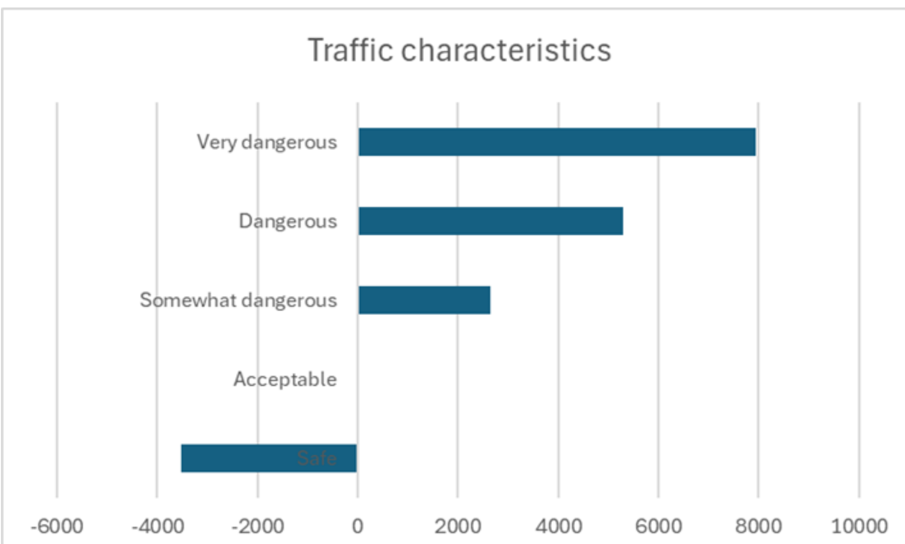


Figure B.1 Traffic characteristics interval scale

Table B.1 Performance level (Street Direction-Speed Limit-Traffic volume- Number of lanes)

Safe	Acceptable	Some-what dangerous	Dangerous	Very dangerous
• One or two way-15- Low-one or two lanes • One or two way-15- Medium-one or two lanes • One or two way-20- Low-one or two lanes • One way-30- Low-One lane • Two way- 10- Low-2 lanes • Two way- 10- medium-2 lanes • Two way- 30- Low-2 lanes • Pedestrian roads	• One way-20-Medium-one lane • One way-30-Medium • One way-30s- Low • One way-40- Low-One lane • Two way- 20-medium • Two way-30s- Low • Two way-30-Medium-two lanes • Two way-30- low-3 or more lanes • Two way-30- High-two lanes • Two way-40- Low-two lanes	•One way-20- High-2 lanes •One way-20- very High-one lane •One way-30- High •One way-30s- Medium •One way-40- Low- 2 lanes •One way-40- Medium- one lane •One way-40- High- one lane •One way-40- Very high- one lane •One way-50- Low- One or two lanes •One way-60- Low •Two way-30s- low- 4 lanes •Two way-30s- Medium •Two way-30- Medium-3 lanes •Two way-30- High-3 lanes •Two way-30- Very high-2 lanes •Two way-30s- High •two way-40- Low- More than two lanes •Two way-40- Medium or high- two lanes •two way-50- Low-two lanes •two way-60- Low •Two way-30- Low- More than 4 lanes	•One way-30s- High •One way-40- Low-More than three lanes •One way-40- Medium-two or three lanes •One way-40- High-two lanes •One way-40- Very High-two lanes •One way-50- Low- more than 3 lanes •One way-50- Medium- One or two lanes •One way-50- High-One or two lanes •Two way-30- Medium-More than 3 lanes •Two way-30s- High-More 2 lanes •Two way-30s- Medium-More 2 lanes •Two way-30- High or very high- More than 3 lanes •Two way-40- Medium- More than 2 lanes •Two way-40- High- three lanes •Two way-40- Very high- Two lanes •Two way-50- Low- More than 2 lanes •Two Medium •Two way-50- High-two lanes	•One way-50- Very High-more than 3 lanes •One way-50- High-more than 3 lanes •One way-50- Very High-more than 3 lanes •Two way-60- Medium-More than one lanes •Two way-60- High-More than one lanes •Two way-60- Very High •two way-70- Low •Two way-70- Medium •Two way-70- High •Two way-70- Very high •One way-40- Medium-More than 3 lanes •Two way-40- High-More than 3 lanes •One way-40- High-More than 3 lanes •One or two way-40- Very high- More than 3 lanes •One way-30- High-More than 3 lanes •One way-30- Very high-More than 3 lanes •One or two way-30s- Very high- More than 3 lanes •Two way-50- High- more than two lanes

Presence of heavy vehicle

This criteria are measured by number of small truck, heavy truck and buses at each street segment per day. This is the only quantitative criteria for segment MCDA model.

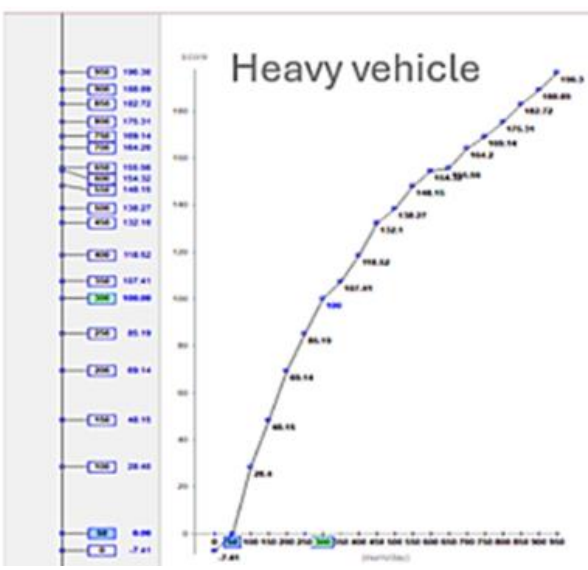


Figure B. 2 Heavy vehicle scale

Visibility

The criteria are based on driver visibility and combines the number of streets lanes with the presence of trees on the street.

Measurement:

Number of lanes: 1-6

Presence of trees: Yes/No

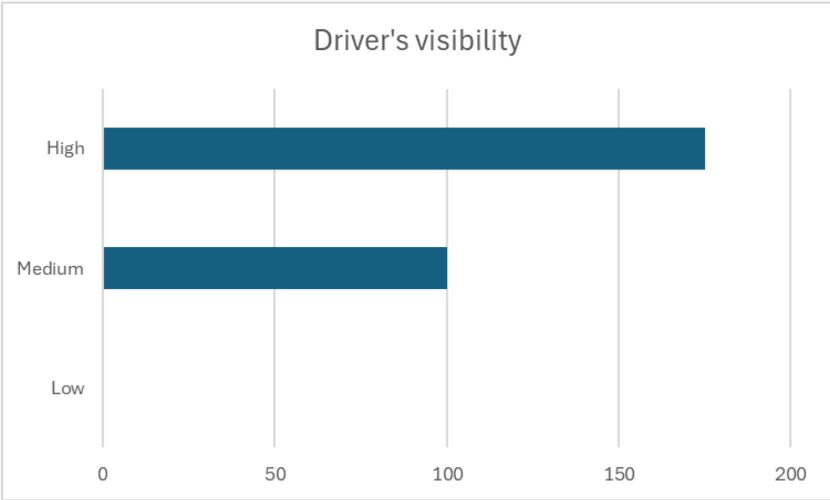


Figure B. 3 Visibility interval scale

Table B.2 Performance level- (presence of tree- Number of street lanes)

Low	**Medium**	**High**
Tree- 1	Tree-3	No tree- 3
Tree-2	No tree- 1	No tree- 4 or more than 4
	No tree- 2	Tree-4
		Tree- more than 4

Traffic calming

This criteria are based on the number and type of traffic calming measures in specific buffer of streets.

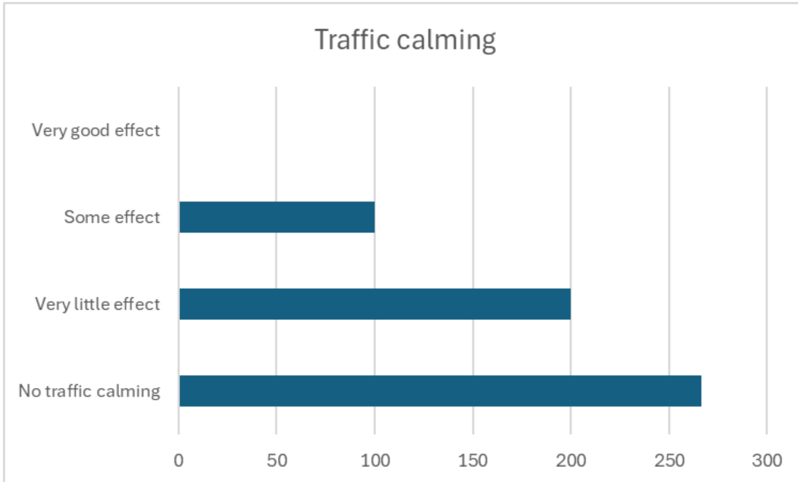


Figure B.4 Traffic calming interval scale

Table B.3 Traffic calming performance level

No traffic calming	Very little effect	Some effect	Good effect
	Speed feedback sign	Bollard	In street sign- Bollard
	Median separation	Permanent speed bump	In street sign- Permanent speed bump
	Street buffer zone	Temporary speed bump	In street sign- temporary speed bump
		Traffic direction change	In street sign- Traffic direction change
		In street sign-Speed feedback sign	Speed feedback sign-Permanent speed bump
		In street sign- street buffer zone	Speed feedback sign-Median separation
		Bollard-speed feedback sign	Speed feedback sign-street buffer zone
		Speed feedback sign-Temporary speed bump	Permanent speed -Traffic direction change
		Permanent speed bump-Temporary speed bump	Traffic direction change-Permanent speed bump
		Speed feedback sign-Traffic direction change	Median separation- Permanent speed bump
		Street buffer zone-Bollard	Permanent speed bump-Bollard
			Median separation/Bollard
			In street sign- Permanent speed bump
			Permanent speed bump-In street sign
			Permanent speed bump-Temporary speed bump
			In street sign-Speed feedback sign-Permanent speed bump
			In street sign-Bollard-Permanent speed bump

Presence of Point of interest- Commercial area size

This criteria are a combination Number of Point of interest and Size of commercial area (meter square) in specific buffer the streets.

Measurement:

Point of interest: "point of interest" typically refers to a specific location or area within an urban environment that is of particular significance or interest due to its unique characteristics, importance, or relevance to the community and its development. Some examples of POI are Cultural and recreational facilities, Transport hubs, Healthcare centers, …

Number of points of intersect in 50-meter buffer of street:

- Low; 1-3
- Medium 4-6
- High7-9 Commercial size; (m^2/ft^2)

The area of the commercial area that intersects with the segment's buffer.

- Small; 36-474 m^2/387.5-5102 ft^2
- Medium 475-7249 m^2/5102-78027 ft^2
- Big >7249 m^2/78027 ft^2

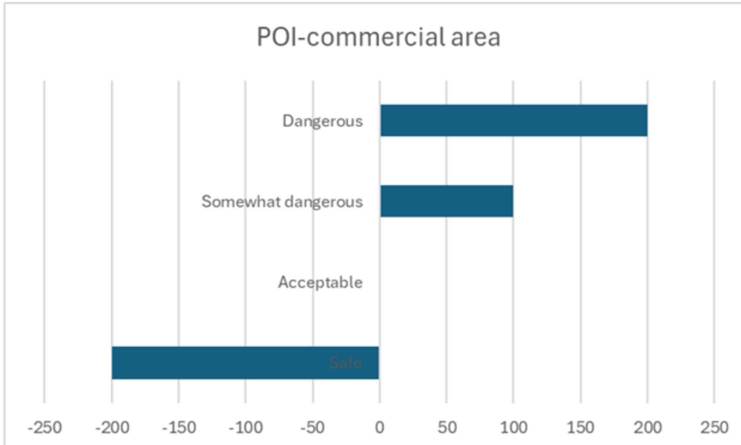


Figure B.5 POI-Commercial area size interval scale

Table B.4 POI-Commercial area size performance level

Safe	Acceptable	Some-what dangerous	Dangerous
• 0-0 • 0-small • Low-0 • Low-Small	• Medium-Small • High-Small • Medium-0	• Low-Medium • 0-Medium • High-0 • Medium-Medium	• Low-Big

Driver's behavior

This criteria are related to the level of drivers' respect to speed limit, stop sign and traffic signal.

Measurement:

- Full respect (FR)
- Adequate respect (AR)
- Moderate disrespect (MD)
- Strong disrespect (SD)

Figure B.6 Drivers' behavior interval scale

Table B.5 Performance level, speed limit/stop sign/traffic signal

Very low	Low	Medium	High
• FR/ FR/FR	• FR/ MD/FR	• AR/MD /MD	• MD/ FR /MD
• FR/ AR/FR	• FR/ FR /MD	• MD/FR /FR	• MD/ MD /FR
• FR/ FR/ AR	• FR/MD/ AR	• MD/ AR /FR	• MD/AR /MD
• FR/ AR/AR	• FR/AR/MD	• MD/ FR /AR	• MD/ MD /AR
	• AR/ FR /FR	• MD/ AR /AR	• MD/MD /MD
	• AR/ FR /AR		• SD to speed limit
	• AR/ AR /FR		• SD to stop sign
	• AR/AR /AR		• SD to traffic signal
	• AR,/ FR /MD		
	• AR/MD /FR		
	• AR/MD /AR		
	• AR/ AR/MD		

APPENDIX C ASSESSMENT OF DRIVERS' COMPLIANCE WITH TRAFFIC REGULATIONS IN MONTREAL

Objective:

The objective is to assess the level of compliance among drivers in Montreal with regard to traffic controls and speed limits.

Methodology:

An online survey was conducted using Lime Survey with residents of Montreal. Recruitment was facilitated by Leger, a firm specializing in public opinion polls in Canada. Participants were selected from Leger's proprietary database, and each was assigned a unique identifier or "token" to maintain confidentiality and link responses accurately. To ensure a representative distribution of responses, limits were set for each postal code and gender according to population statistics from the 2021 Census. The target was 1,000 responses; however, 1,028 were collected.

Data Collection:

The survey comprised four sections:

1. Demographics: Participants provided their postal code and duration of residency and some general sociodemographic question.
2. Speed Limit Adherence: Participants ranked the general adherence to speed limits in their neighborhood on a scale from very low to very high, and answered detailed questions about the frequency and extent by which drivers exceed speed limits.
3. Traffic Control Respect: Participants rated the respect for traffic lights and stop signs generally and also answered detailed questions about the frequency and extent of violations.
4. Pedestrian Priority: This section focused on safety concerns regarding pedestrian crossings to evaluate the level of respect drivers show towards pedestrian right-of-way.

The frequency options were designed for better categorizing the final results. Understanding the frequency of violations helps quantify the severity and regularity of non-compliance, thus providing a clearer analysis of drivers' behaviors:

Low frequency: yearly and essentially never. (For speed limit low frequency is essentially never since even a very low frequency of exceeding speed limit is very dangerous)

Medium frequency: weekly, monthly, (for speed limit yearly and monthly)

High frequency: daily, (for speed limit weekly)

Very high frequency: always (for speed daily, always)

Data Cleaning and Results Extraction:

Responses were classified into four categories based on adherence levels: full respect, acceptable respect, moderate disrespect, and strong disrespect. Each category was defined by frequency of non-compliance, ranking, and percentage by which drivers exceed speed limits. Table C.1 illustrates the details of classification.

Table C-1 Variables' classification

Level/variable	Speed limit	Stop sign	Traffic light	Crossing
full respect	Low frequency Ranking:90-100 Speed exceeding: 1-5	Low frequency Ranking:90-100	Low frequency Ranking:90-100	Low frequency Ranking:90-100
acceptable respect	Medium frequency Ranking:75-89 Speed exceeding: 5-9	Medium frequency Ranking:75-89	Medium frequency Ranking:75-89	Medium frequency Ranking:75-89

Table C-1 Variables' classification (continued).

moderate disrespect	**High frequency** **Ranking:50-74** **Speed exceeding: 10-14**	**High frequency** **Ranking:50-74**	**High frequency** **Ranking:50-74**	**High frequency** **Ranking:50-74**
strong disrespect	Very high frequency Ranking: More than 50 Speed exceeding: more than 15	Very high frequency Ranking: More than 50	Very high frequency Ranking: More than 50	Very high frequency Ranking: More than 50

APPENDIX D DRIVERS' BEHAVIOIR SURVEY

Participants characteristics

Table D-1 Participants characteristics

Gender	Frequency	Proportion (%)
Female	552	50.09
Male	547	49.64
Other	3	0.27
Age	**Frequency**	**Proportion (%)**
Under 18	6	0.54
18-24	53	4.81
25-34	197	17.88
35-44	206	18.69
45-54	117	10.62
55-64	209	18.97
More than65	314	28.49
Income	**Frequency**	**Proportion (%)**
Under $15,000	55	4.99
Between $15,000 and $29,999	133	12.07
Between $30,000 and $49,999	191	17.33
Between $50,000 and $74,999	233	21.14
Between $75,000 and $99,999	167	15.15
Between $100,000 and $150,000	209	18.97
Over $150,000	114	10.34
Household Size	**Frequency**	**Proportion (%)**
1	366	33.21
2	595	53.99
3 or more	138	12.52
Prefer not to say	3	0.27
Ethnicity	**Frequency**	**Proportion (%)**
Other North American origins	462	41.92
European origins	393	35.66
Middle East origins	37	3.36
African origins	35	3.18
North American Aboriginal origins	33	2.99

Table D-1 Participants characteristics (continued).

Latin, Central and South American origins	28	2.54
Asian origins	27	2.45
Caribbean origins	19	1.72
South-west asian origins	9	0.82
Oceania origins	1	0.09
Prefer not to say	58	5.26
Employment	**Frequency**	**Proportion (%)**
Full-time (more than 30 hours per week)	498	45.19
Part-time/casual job	88	7.99
Retired	374	33.94
Student	66	5.99
Not currently employed, but looking for work	35	3.18
Homemaker	34	3.09
Prefer not to say	7	0.64
Travel Mode	**Frequency**	**Proportion (%)**
Car driver	443	40.20
Walking	325	29.49
Public transport	242	21.96
Car passenger	50	4.54
Cycling	31	2.81
Other	9	0.82
Motorized two-wheel vehicle	2	0.18
Having children	**Frequency**	**Proportion (%)**
No	686	62.25
Yes	416	37.75

APPENDIX E INTERSECTION CRITERIA DESCRIPTION

Segment danger level

This criteria are based on the danger level (from the segment MCDA model) of segments reaching each intersection.

Measurement:

Segment danger level (safe, acceptable, somewhat dangerous, dangerous, very dangerous)

Table E-1 Performance Level-Segment danger level

Safe	Acceptable	Somewhat dangerous	Dangerous	Very dangerous
• 3way- all safe • 4way-all safe • 3 way-one acceptable, two safe • 4way- one acceptable, three safe	• 3way- all acceptable • 4way- all acceptable • 3 or 4 way – one somewhat dangerous , the other streets safe or acceptable • 3way- 2 acceptable,1 safe • 4way-2 acceptable, 2 safe	• 3way- all Somewhat dangerous • 4way- all Somewhat dangerous • 3 or 4 way – one dangerous, the other streets safe or acceptable, Somewhat dangerous • 3way- 2 Somewhat dangerous,1 safe or acceptable • 4way-2 Somewhat dangerous, 2 safe or acceptable	• 3way- all dangerous • 4way- all dangerous • 3 or 4 way – one very dangerous, the other streets safe or acceptable, Somewhat dangerous • 3way- 2 dangerous,1 safe or acceptable • 4way-2 dangerous, 2 safe or acceptable	• 3way with two or more very dangerous • 4 way with two or more very dangerous • 3way- one very dangerous-2 dangerous • 4way- one very dangerous- 2 or more dangerous

Intersection design

The criteria include two variables: the number of streets that reach an intersection and the type of streets that reach it.

Measurement:

- Type of intersection (three way or four way)

- Street classification

L= local

P= pedestrian

C=collector

A= Arterial

Table E-2 Performance level- Intersection design

Low	Medium	High	Very high
• 3-way- L-L-L • 3way-P-L-L • 4way-L-L-L-L • 4way-L-L-L-P • 4way-P-P-L-L	• 3-way-C-L-P • 3way-C-L-L • 4way-L-L-L-C • 4way-P-L-C-C	• 3-way- C-A-P • 3way-A-C-L • 4way-L-L-L-A • 4way-A-C-C-L • 4way-A-C-L-L • 4Way-A-L-L-L • 4WAY-C-C-C-L • 4WAY-C-C-C-P • 3way-C-C-C	• 3-way - A-A-A • 3way- A-C-C • 3way- C-A-A • 4way- P-L-A-A • 4way-A-C-C-C • 4WAY-A-A-C-C • 4WAY-A-A-L-L • 4WAY-A-A-A-C • 4WAY-A-A-A-A • 4WAY-C-C-C-C • 3way-L-A-A

Traffic control

This criteria are based on the type of traffic control.

Table E-3 Performance level- Traffic control

Low	Medium	High	Very high
• All way stop sign	• Traffic signal with pedestrian light	• Traffic signal	• No stop sign- No traffic signal

Bike path design

Based on the criteria, I was evaluating the impact of the presence and type of bike paths on pedestrian safety among children.

Table E-4 Performance level- Bike path design

No bike path	Little effect	Some effect
	• Bande cyclable • Chaussée désignée • Non déterminé • Voie partagée Bus-Vélo	• Piste cyclable au niveau du trottoir • Piste cyclable en site propre • Piste cyclable sur rue • Sentier polyvalent • Vélorue

Presence of point of interest & Commercial area size

This criteria are a combination type of Point of interest and Size of commercial area (meter square) in specific buffer the streets.

Measurement:

Point of interest: "point of interest" typically refers to a specific location or area within an urban environment that is of particular significance or interest due to its unique characteristics, importance, or relevance to the community and its development. Some examples of POI are Cultural and recreational facilities, Transport hubs, Healthcare centers, …

Commercial size; (m^2/ft^2)

The area of the commercial area that intersects with the segment's buffer.

- Small; 36-474 m^2/387.5-5102 ft^2
- Medium 475-7249 m^2/5102-78027 ft^2
- Big >7249 m^2/78027 ft^2

Table E-5 Performance level- Type of POI & commercial area size

Low	Medium	High	Vey high
• 0-0 • Public Art-0 • Public Art-small • Building & Landmark-0 • Library-0 • Library-small • Cultural Establishment-o • Venue-0 • Park & Other Green Space-0 • Park and other green space-small • Government Service-0 • Municipal Service-0 • Municipal Service-small	• Library-medium • Community Equipment-0 • Community-small equipment • Municipal-Medium Service • Transport-0 • Sports & Recreation Equipment-o • Government Service-Medium • Public-medium art • Cultural-small establishment • Medium-cultural establishment • Venue-small • Venue-Medium • Building & Place of Interest-Medium • Emergency Department-0 • Emergency Department-small • Park and other green-medium space • Health Service-0 • Health Service-small	• Health Service-Medium • School-0 • School-small • School-medium • Community-Medium Equipment • Sports & Recreational Equipment-Medium • Transport-small • Transport-medium • Emergency-Medium Service	• Community-big equipment • Emergency-big department • Sports & Recreational-Big Equipment • Building & Interest-Big • Park and other green space-big • Venue-big

Traffic calming

This criteria measured based on the number and type of traffic calming measure in specific buffer on intersection.

Table E-6 Performance level- Traffic calming

Very little effect	**Some effect**	**Good effect**
Avancée de trottoir virtuelle/Virtual curb extension-	**Curb extension** **In street sign** **Pedestrian Refuge**	**Elevated intersection** • **Pedestrian Refuge - curb extension** • **Elevated Intersection - curb extension** • **Curb extension – In street sign** • **Elevated Intersection - Curb extension - Removable marker** • **Virtual curb extension- Curb extension**

Intersection visibility

The criteria is based on how visible children are on the street as pedestrians.

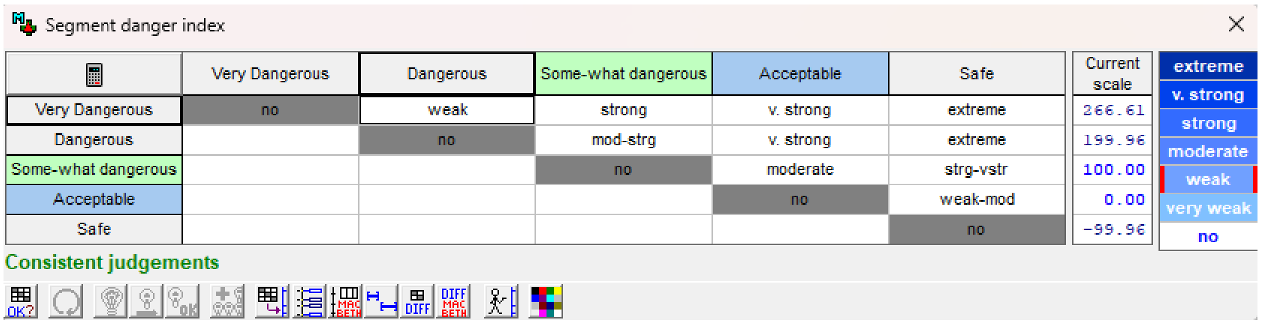
Measurement:

- Presence of parked vehicle

Table E-7 Performance level- Intersection visibility

Low visibility	Medium visibility	High visibility
• All street - two side	• One side	• No parked vehicle

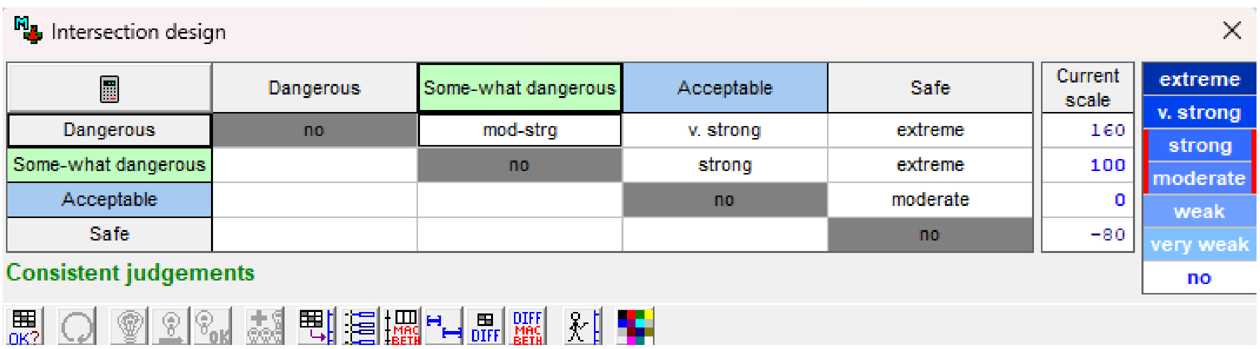
APPENDIX F VALUE JUDGEMENTS-INTERSECTION



Segment danger index

	Very Dangerous	Dangerous	Some-what dangerous	Acceptable	Safe	Current scale
Very Dangerous	no	weak	strong	v. strong	extreme	266.61
Dangerous		no	mod-strg	v. strong	extreme	199.96
Some-what dangerous			no	moderate	strg-vstr	100.00
Acceptable				no	weak-mod	0.00
Safe					no	-99.96

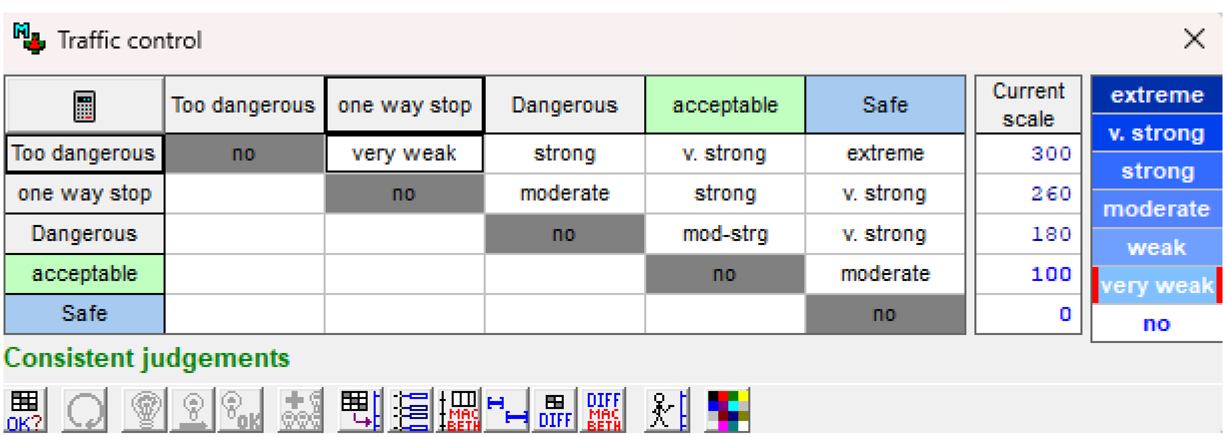
Figure F.1 Segment danger level



Intersection design

	Dangerous	Some-what dangerous	Acceptable	Safe	Current scale
Dangerous	no	mod-strg	v. strong	extreme	160
Some-what dangerous		no	strong	extreme	100
Acceptable			no	moderate	0
Safe				no	-80

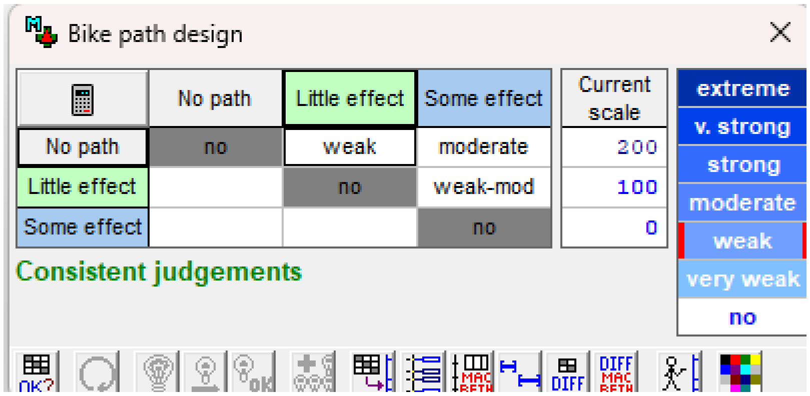
Figure F.2 Intersection design



Traffic control

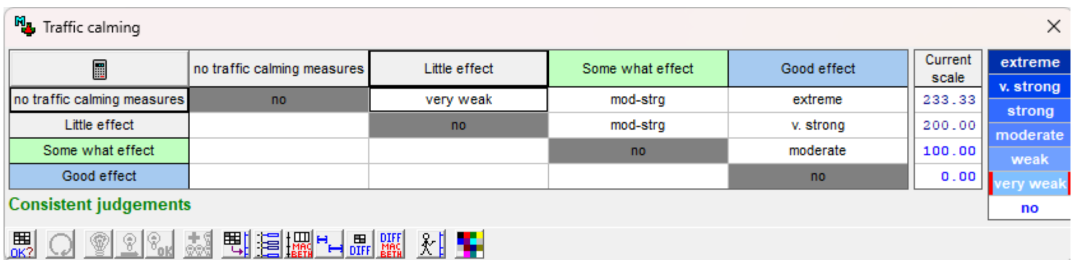
	Too dangerous	one way stop	Dangerous	acceptable	Safe	Current scale
Too dangerous	no	very weak	strong	v. strong	extreme	300
one way stop		no	moderate	strong	v. strong	260
Dangerous			no	mod-strg	v. strong	180
acceptable				no	moderate	100
Safe					no	0

Figure F.3 Traffic control



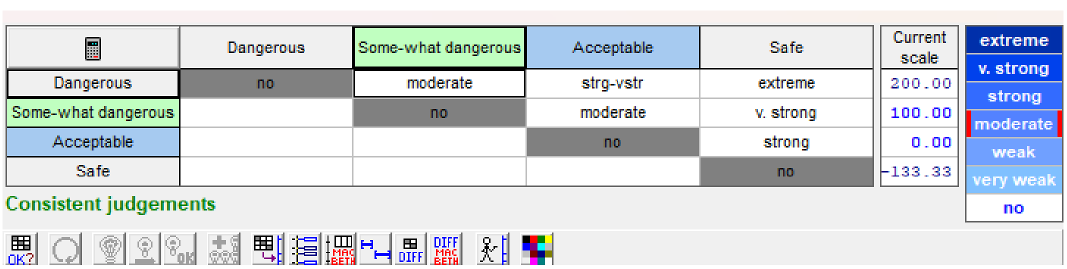
	No path	Little effect	Some effect	Current scale
No path	no	weak	moderate	200
Little effect		no	weak-mod	100
Some effect			no	0

Figure F.4 Bike path design



	no traffic calming measures	Little effect	Some what effect	Good effect	Current scale
no traffic calming measures	no	very weak	mod-strg	extreme	233.33
Little effect		no	mod-strg	v. strong	200.00
Some what effect			no	moderate	100.00
Good effect				no	0.00

Figure F.5 Traffic calming



	Dangerous	Some-what dangerous	Acceptable	Safe	Current scale
Dangerous	no	moderate	strg-vstr	extreme	200.00
Some-what dangerous		no	moderate	v. strong	100.00
Acceptable			no	strong	0.00
Safe				no	-133.33

Figure F.6 Type of POI & Commercial area size

Intersection Visibility

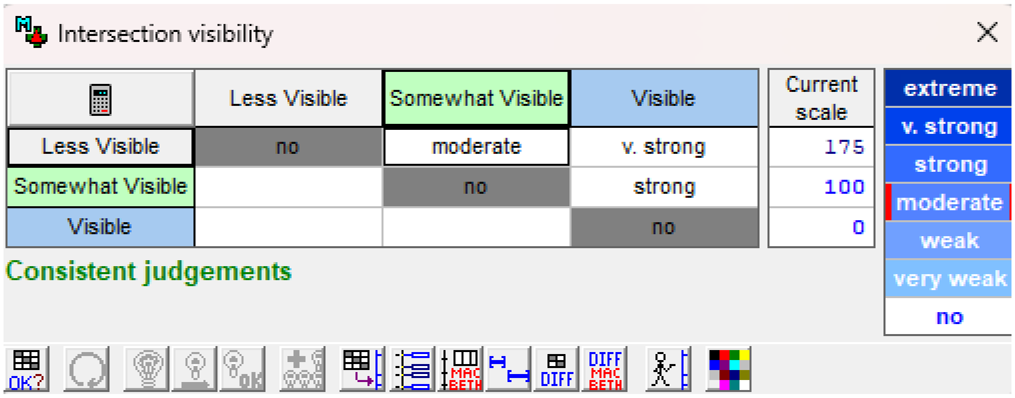


Figure F.7 Intersection visibility

APPENDIX G: DATA SOURCE

Table G.1 Data description

Variable	Measurement	Data Source
Speed	Speed limit: extracting the speed limit from the **Sign dataset**	https://donnees.montreal.ca/
Street direction	Extracting from '**Géobase - réseau routier**' dataset	https://donnees.montreal.ca/
Number of lanes	Extracting from Street dataset	https://www.openstreetmap.org/
Number of bus	Calculating number of bus at each street segment using '**Bus stop**' dataset and **Bus route** dataset	https://donnees.montreal.ca/
Number of heavy vehicle	• Calculation using **Vehicle, cyclist and pedestrian counts at intersections with traffic lights (with camera)** dataset • **Estimation of remaining street segment using BE variables**	https://donnees.montreal.ca/ Estimation data
Presence of trees	Extracting from **Public trees** dataset	https://donnees.montreal.ca/
Traffic calming	**Traffic calming** dataset for intersections and street segments	Prepared by City of Montreal
Point of intersect	**POI** dataset	https://www.donneesquebec.ca/
Commercial area	Aggregation of different commercial dataset **POI** dataset	https://www.openstreetmap.org/ https://www.donneesquebec.ca/
Stop sign	Extracting the speed limit from the **Sign dataset**	https://donnees.montreal.ca/
Traffic signal	Extracting from **Traffic signals** dataset	https://donnees.montreal.ca/
Type of street (local, collector, arterial)	Extracting from '**Géobase - réseau routier'** dataset (street class section)	https://donnees.montreal.ca/
Shape of intersection	Extracting from **Géobase-Nodes** dataset	https://donnees.montreal.ca/
Bike path design	Extraction from **Bike path** dataset	https://donnees.montreal.ca/
Presence of parked vehicles	Extraction from **On-street parking signs** dataset	https://donnees.montreal.ca/
Traffic volume	Average Annual Daily Traffic (AADT)	Simulation data
Borough (City of Montreal)	**Neighborhood** dataset	https://www.openstreetmap.org/
Census block	**Census block**	https://www.statcan.gc.ca/