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Transportation Research Procedia 76 (2024) 13–24

Transportation Research Procedia

www.elsevier.com/locate/procedia

12th International Conference on Transport Survey Methods

Multi-frame sampling in household travel surveys: a Montreal case study

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Abstract

The latest household travel survey held in Montreal in 2018 included important methodological innovations with the sampling strategy. This paper first provides a portrait of the household survey samples and frames. It reports on the sample integration mechanisms adapted to the multi-frame approach and presents the strategies used to integrate data from various sampling frames. 13 different frames were used in this survey with some overlapping and time period issues. The article also presents the weighting method used for combining samples. The results show that the methods used made it possible to correct the main issues of the samples collected.

Keywords: travel survey;multi-frame survey;survey bias;weighting and ajustement methods

1. Introduction

Travel survey methods have entered an era of change in recent years. New technologies such as mobile phone, GPS or web possibilities offer new opportunities compared to standard survey methods. These can be used to gather new information, to reduce respondent burden and/or provide an alternative to the respondents to facilitate their recruitment. Combining various approaches and sampling frames, as was the case for the 2018 Montreal survey, is also preferable to more easily reach population segments that are difficult to reach or have a high rate of non-response. Using such approaches though raises several challenges with respect to data integration related to the multiplication of survey frames and increased risk of bias. Still, declining response rates faced with standard methods and the difficulty in recruiting a sufficient and representative number of respondents encourages the experimentation of new techniques. Yet, processing the collected data becomes more complex and, as a result, the integration process required to obtain a coherent data set, quickly becomes a difficult puzzle to solve.

While it is desirable to obtain more representative and better-quality data, it is important to develop consistent methods to properly integrate the data coming from various survey methods or sampling frames. Several theoretical methods exist. However, it may be difficult to strictly apply them in practical transport surveys. For example, when working with several sampling frames in surveys, several elements are to be taken into consideration such as the

10.1016/j.trpro.2023.12.034

probability of being selected, the size of the frames, the identification of frame units or the presence of a unit in more than one frame. It is sometimes difficult to obtain the necessary information to address these different issues.

The greater Montreal area (GMA) is characterized by a rapid increase of households with only cell phones and a decrease of households with landline phones. As of 2016 (CRTC, 2018), in Canada, 88.0% of households owned at least one cell phone, with an average of 1.6 cell phone numbers by household. In addition, 32.5% of households solely have cell phones in their household. Historically, the Montreal surveys used to rely on a single sampling frame; but new approaches were used in the latest survey conducted in 2018. These were primarily aimed at ensuring that recruitment objectives were met, as well as countering various sampling bias related to the use of a single frame that is not totally representative of the target population. In the 2018 survey, several frames, including phone numbers (landline and cell phone), household addresses, lists gathering members of mobility services (carsharing for instance) and lists of employees and students from several universities were used to maximize and diversify the recruitment of respondents. The use of all these frames in one survey raises questions about data and sample integration.

This paper first provides a portrait of the 2018 Montreal household survey samples and frames. It then reports on the sample integration mechanisms in multi-frame survey and presents strategies used for integrating data in the Montreal case. Finally, this paper raises the different issues and challenges using multi-frame survey in transportation surveys.

2. Background

A frame in a survey is usually a list of sampling units. (Lohr, 2007) A random sample can then be collected from this frame where the inference will be based on the probability of being chosen in the frame assuming that the frame represents the entire target population. However, in order to cover the entire reference population, reduce costs or increase the response rate, the use of several sampling frames becomes an interesting alternative. However, the overlap of sampling frames, i.e. the sampling units that are found in more than one frame, must be taken into account in the calculation of probabilities. For example, for a phone survey with 2 frames, namely landlines and cell numbers, a household with a landline and two cell phones would be more likely to be contacted to complete the survey.

When using a multi-frame survey, it is more difficult to estimate indicators using the combined samples. If there is overlap between at least two frames, estimating weights for units included in this overlap requires more complex methods. A frame refers to the list of units (persons or households) in a target population. Several approaches exist to combine samples from multiple frames (Lohr and Rao, 2006). The first method consists of estimating a composite weight factor for units into two or more frames. Several techniques have been developed as the Fixe Weight Estimator (FEW) (Hartley, 1962), the screening estimator or other methods based on the estimator variance minimization (Hartley, 1974) (Fuller and Burmuester, 1972), (Skinner and Rao, 1996), (INSEE, 2017).

These methods each has advantages and disadvantages. The most appropriate method depends on the number of sampling frames used in the survey, the types of disjoint domains obtained and the information available for each of the sampling frames (number of units, etc.). However, these techniques require the ability to estimate the membership of a unit of a sampling frame to all other sampling frames. It is therefore necessary to have access to all the units of the sampling frames and not only a sample. In addition, it is also necessary to have access to information to identify which sampling frames a unit belongs to. Some of these methods can be used when using more than two frames but others are limited to only two frames. The more frames are used, the more difficult these techniques are to use and adapt. In addition, the use of more than one frame will automatically increase the complexity of the data processing and weighting steps and may, in some cases, increase the costs of data collection (Sharp & Murakami, 2004).

Another possible technique is the Single Frame Estimator (SFE) (Bankier, 1986, Kalton and Anderson, 1986). This technique estimates an adjustment factor, for units belonging to more than one frame, that is inversely proportional to the likelihood of being selected for the entire combined frame. Fahimi (2014) recommends estimating an adjustment factor to correct for the multiplicity of a unit in a frame, the number of occurrences of a unit within the same frame. For instance, a household with two cell phone numbers would appear twice in the frame). Usually, this adjustment factor is applied to the initial weight factor and corresponds to the inverse of the unit's multiplicity. The SFE method is in a way a generalization of this adjustment to the use of more than one sampling frame.

While it is difficult to find examples in the literature of multi-frame surveys as complex as the Montreal one, some case studies are interesting to point out (Elkasabi, 2015, Verreault and Morency, 2018). Baffour et al. (2016) tested different methods to combine samples, namely the fixed weight Estimator, the screening estimator, the estimator variance minimization, and the single frame estimator, from a survey in Australia with a total sample of 2015 respondents. They conclude that the best approach to use depends essentially on the quality of the information available at the frame level as well as on the respondents belonging to each frame. Benford et al., 2009 explore biases on different indicators related to the inclusion and exclusion of a cell phone number-based frame in a survey initially containing a single landline frame. Authors are particularly interested in the weighting of samples for the estimation of indicators. They conclude first that the use of multiple frames in a survey makes the estimates more robust, which is desirable. Although the different methods tested give differences in the estimated indicators, they mention that it is difficult to assess which solution gives the most representative results of the target population. Vicente (2009) studies the impact of adding a cell phone sampling frame on the estimation of different sociodemographic indicators. Although the impact of adding the sample from the cell frame are described as minor, the author also indicates that the method to be used to combine the samples must depend on the degree of precision required in the estimates. Lo et al. (2017) studied the unweighted sample from the Toronto 2016 TTS survey which had 3 frames. They conclude that the combined samples are more representative of the reference population than the sample from each of the sampling frames. The address-based sampling frame is assessed to be the most representative of the reference population.

3. Montreal case study

3.1. Data

Data used in this paper includes samples collected during the Montreal 2018 travel survey. In the Montreal area, household surveys have been conducted approximately every 5 years since 1970. The 2018 survey was aiming to recruit 77,000 households with a sampling rate of 4%. Survey area covers 10,000 km² and contains a population of more than 4 million people. Montreal's travel survey is historically conducted using a computer-assisted-telephone-interviewing platform (CATI). In 2013, a computer-assisted-web-interviewing (CAWI) component was integrated for the first time as a pilot project. This component took more importance in 2018. The Montreal surveys also rely on proxy respondents: only one person answers for all household members. The purpose of the questionnaire is to collect and measure the mobility of all household members during the last business day preceding the interview. The questionnaire includes several questions about the household (motorization, home location, size, income), sociodemographic characteristics of household members (age, gender, main occupation, mobility tools, driving license, transit subscription, bikesharing subscription, carsharing subscription) and information about trips made (mode, trip purpose, departure time, origin and destination). Both questionnaires (CATI and CAWI) are very similar. Although some methodological elements evolved through surveys, they have remained fairly constant over time, with the aim of obtaining comparable indicators. However, methodological comparability does not ensure comparable survey outcomes when significant changes occur regarding response rates, population coverage, recruitment methods, etc. For example, the coverage rate of the main sampling frame (landline) has steadily declined over the past decade. It is difficult to assume now that this sampling frame is still representative of the entire target population.

3.2. 2018 survey frames and samples

The Montreal 2018 household survey therefore corresponds to the beginning of a paradigm shift for survey methodology in the Montreal region. Historically, the recruitment of respondents was based solely on landline telephone directories. The 2013 survey had timidly initiated the use of multiple frames with the use of cell phone numbers for part of the sample. However, the samples collected from cell phones and landline phones were mutually exclusive because only households that did not have landlines could belong to the cell phone sample. This decision was taken in order to simplify the integration of the two samples afterward. At the same time, with the response rates generally declining and the difficulty in recruiting samples, can we refuse people who wish to answer?

To collect a larger and more representative sample of the population and to fill in the gaps in the frame used historically, the 2018 household travel survey multiplied sampling frames used as well as the recruitment methods. The frames that were used are as follows.

1. Telephone directory: Includes households with one or more landlines available in telephone directories. Phone numbers not listed in the directory are excluded from this frame. The address linked to each of the telephone numbers is available. This frame is the main one for the 2018 survey.
2. Addresses: Includes households where at least 1 person is listed on the elector list. In addition, invitations were sent to addresses that were not present in the main frame.
3. Cell phone directory: Includes people with a valid cell phone number that is available in the provider's lists. The provider ensures that the respondent does not have a landline at home for these cell phone numbers.
4. Universities: Includes students and employees of 4 universities in the region.
5. Carsharing members
6. Bikesharing members

The main objective of using more than one sampling frame was to increase the number of sampled households and to have a more representative sample of the reference population. Another specific objective of this study was to increase the sample for the 18 – 30 years old who was under sampled in the previous survey. Some of the frames, such as cell phone numbers, carsharing, bikesharing and university students, specifically target this sub-population. It should be noted that in 2018, two main carsharing companies were operating in the region, Car2Go and Communauto. Only the members of Communauto were solicited. Table 1 summarizes the characteristics of every survey frame used in the 2018 travel survey.

Table 1 Characteristics of the sampling frames in the 2018 household survey

#	Frames	Time frame	Overlapping frames	Mode	Recruitment	Sample	Frame total units
1	Landline	September to December	4, 5, 6	CATI	List	56,482 (75.28%)	477,761
2	Address	October to December	3, 4, 5, 6	CAWI	List	6,209 (8.08%)	100,800
3	Cell phone	October to December	2, 4, 5, 6	CATI	List	10,744 (14.17%)	100,000
4	Universities	November to December	1, 2, 3, 5, 6	CAWI	Email	1,379 (1.85%)	147,389
5	Carsharing members	November to December	1, 2, 3, 4, 6	CAWI	Email	442 (0.59%)	16,420
6	Bikesharing members	November to December	1, 2, 3, 4, 5	CAWI	Newsletter	24 (0.03%)	30,573

Another issue of the 2018 household survey is the different time periods according to the sampling frames. A provincial election was held in October 2018 and the government strongly recommended not to conduct a household survey during the election campaign. This has therefore delayed the use of certain frames in time. Several of the frames overlap with others. This aspect can increase the likelihood of being selected for the survey or result in double response. The overlap of the sampling frames as well as the belonging of the sampled households to all the sampling frames are therefore important elements to be addressed in the combination methodology. Specific questions on cell phone and landline ownership, carsharing and bikesharing subscriptions have therefore been added to the questionnaire to facilitate the allocation of a sampled household to various sampling frames. In addition, the usual place of work and study reported by respondents was used to derive household membership from the frames of the various universities targeted.

As can be seen in Table 1, the main sampling frame remains that of fixed lines with 75.28% of the households sampled, followed by the address and cell phone database with 8.08% and 14.17% respectively. The overlap issues are therefore mainly with the sampling frames concerning universities and carsharing and bikesharing members which correspond to 2.47% of the sampled households. Although these last 3 samples are small compared to those of the three main sampling frames, they can have a significant impact on some specific indicators if overlap is not considered in the integration of samples.

Table 2 shows the distribution of the number of sampled households according to the number of sampling frames to which the household belongs. Samples from different sources all have a certain proportion of their sample that belongs to more than one frame. Some sampled households belong to up to 5 sampling frames. Except for the sample from fixed lines where 95% of the sampled households are linked with a single sampling frame, most of the other sampled households are associated to more than one sampling frame. This confirms that the landline sample is probably not representative of the entire population. Considering only a sample from this frame would lead to significant biases in the results. It should be noted that for the samples from the universities, 4 universities were surveyed and for each, invitations were sent to workers and students. This explains why a large percentage of the sampled households belong to more than 2 sampling frames.

Table 2 Distribution of the number of sampled households according to the number of sampling frames to which the household belongs

Number of sampling frames to which the household belongs	% of households sampled by frequency of frame membership					
	Landline	Cell	Address	Bikesharing members	Car-sharing members	Universities
1	95.5%	0.0%	6.6%	0.0%	0.0%	11.8%
2	4.2%	91.2%	82.1%	29.2%	21.7%	43.1%
3	0.3%	8.2%	10.4%	58.3%	51.4%	38.4%
4	0.0%	0.6%	0.9%	12.5%	24.4%	6.5%
5	0.0%	0.0%	0.0%	0.0%	2.5%	0.2%
Household sampled	56,482	10,744	6,209	24	442	1,379
Frame total units	477,761	100,000	100,800	30,573	16,420	147,389

The sample recruited from each frame made it possible to recruit somewhat different populations. This was one of the objectives of using multiple frames. Figure 1 illustrates the distribution of sampled people by source of recruitment. As mentioned, the distributions of the sampled people are different depending on the frame. The landline frame has an issue with people aged 20 to 35. The sample from cell phones makes it possible to fill the subsample of these age groups. For the university sample, although these samples are smaller in number, they mainly increase the sample of people aged 20 to 25, particularly women.

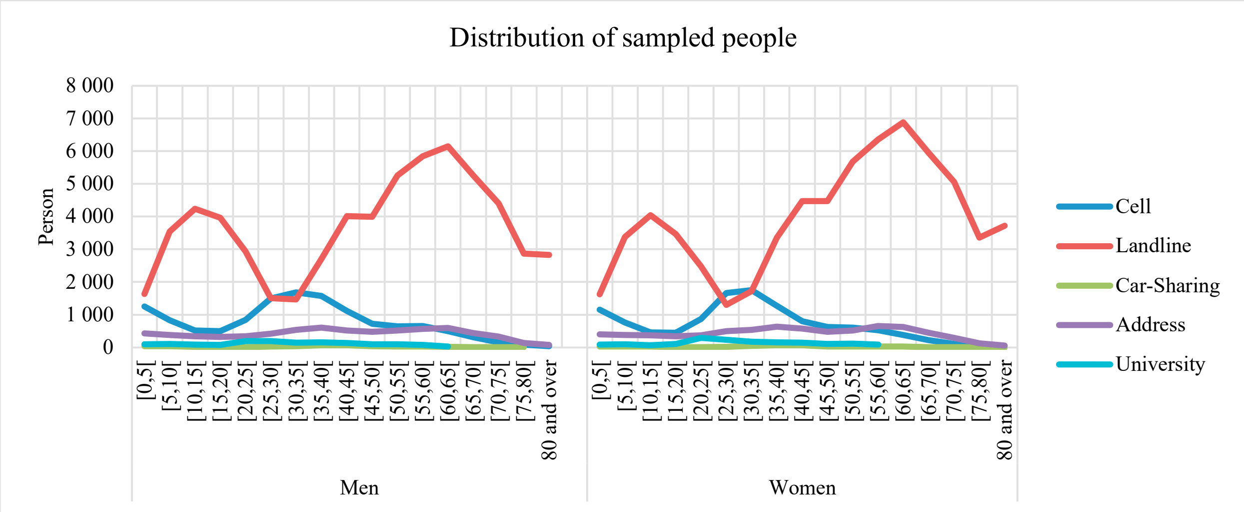

Figure 1 Distribution of sampled people according to the source of recruitment

The characteristics of the sampled households are also somewhat different depending on the sampling frame. Table 3 presents the average characteristic of the sampled households including the number of vehicles owned, the size of the household, the number of children and the average age of the household members. Of course, these characteristics are also dependent on the residential location. However, there are significant differences when comparing samples from sampling frames. The household average age, which varies greatly according to the sampling frame, shows that it is not the same types of households that are sampled.

Table 3 Average household characteristics by sampling frame

Frame	Car	People	Children	household age
Cell	1.28	2.29	0.51	35.80
Landline	1.46	2.30	0.41	54.33
Address	1.38	2.31	0.44	44.50
Bikesharing	0.79	2.17	0.46	33.47
Car-sharing	0.21	2.00	0.42	40.97
University	0.99	2.34	0.45	32.32

3.3. Temporal distribution of the sample

Finally, the different periods of data collection according to the sampling frame provide an additional issue concerning the temporal distribution of the sample during the survey period. Table 4 presents the distribution of the aggregate sample of households by day of the week as well as month. The concept of average weekday assumes that the variability of trip behaviours is not too high between weekdays and months. However, this is not always the case depending on the indicator, walking and cycling for instance. It is therefore important to obtain an equivalent sample distribution over time. Table 4 shows that this is not at all the case when we look at the distribution according to weekdays. However, this is much more problematic for the distribution according to the month, which is far different from the theoretical one that should be obtained when we estimate the number of days surveyed per month. Additional constraints must therefore be included to obtain combined samples that are representative of the survey period.

Table 4 Distribution of sampled households by day and month

Distribution of sampled households			
		Sample	Theoretical
Days of week	Monday	18,7%	20,0%
	Tuesday	19,6%	20,0%
	Wednesday	20,7%	20,0%
	Thursday	18,8%	20,0%
	Friday	22,2%	20,0%
Month	September	8,6%	24,4%
	October	29,2%	28,2%
	November	36,9%	28,2%
	December	25,3%	19,2%

4. Methodology for data integration

The method used to integrate the samples consists of two main steps. The first step is to combine the samples while applying an adjustment for the use of multiple frames. The second step is to weight the samples according to several reference populations and some constraints.

4.1. Adjustment factor for multiframe sampling

The sample combination method is based on the Single Frame Estimator method. The choice of this method was determined by the simplicity of the method. This method requires determining the probability of presence of a sampled unit in the different sampling frames, while the other methods usually require knowing the presence of each unit from the sampling frame to the other sampling frames. It is therefore necessary to obtain the complete list of survey frame units with the necessary attributes in order to identify their membership in each one. This was impossible for us in this study.

The SFE method assumes that a single sampling frame includes all the units to be surveyed. This single frame is simply the sum of all the frames used during the survey. To consider units that are found in more than one frame, an adjustment factor is estimated for those units and is inversely proportional to the probability of a unit to be selected in the frame. It is assumed that the drawing of each sample of units in the frames is random. When using two sampling frames (A and B), the probability (p) of each unit i to be included in the sample is estimated by equation (1).

$$p_i = P_i^A + P_i^B - P_i^A P_i^B \quad (1)$$

This equation is generalized according to all the frames of the 2018 survey, i.e., 13 frames in total by considering the students and employees of the 4 universities as 8 independent frames. It is quite complex to generalize this equation with so much frame because it depends on the presence or absence of the overlap of each frame. However, for a standard case of a sampled household present in 3 frames, the probability (p) can be estimated by equation (2).

$$p_i = P_i^A + P_i^B + P_i^C - P_i^A P_i^B P_i^C \quad (2)$$

To calculate this probability, it is necessary to have the attributes required to determine the belonging of each household to all the sampling frames. Subsequently, the adjustment factor (w) corresponding to this unit (i) is estimated using equation (3):

$$w_i = \frac{1}{p_i} \quad (3)$$

Where p_i is the probability for a household to be selected as a respondent and w_i is the adjustment factor.

These factors are therefore estimated for all sampled households. A household belonging to more than one frame should therefore have an adjustment factor of less than one to account for the fact that it had a greater probability of being selected. The adjustment factor is equal to one for households belonging to a single sampling frame. At the end of the process, we obtain a single sample where each sampled household has an adjustment factor that will be applied initially in the weighting method.

The advantage of this method is that it is simpler and faster to use than the other methods described above. Other methods usually require several attributes that are difficult to obtain about the frames (e.g., enumeration of the units of each of the frames, attributes to determine the membership of each unit in all frames). Nevertheless, this method requires an accurate estimate of the probability, for each unit of the sampling frame, of being selected in the survey. It is therefore necessary to get the attributes about the belonging of each surveyed household to each sampling frame.

4.2. Weighting process

The second step in the methodology is to weight the combined sample while ensuring that the weighted sample meets certain criteria based mainly on reference populations. The main variables describing the reference population used is the sociodemography of people and households as defined by the more recent Canadian census. It includes the number of households by size as well as the number of people by gender and cohort for each geographical strata used. In total, there are 113 geographic weighting strata. In addition to sociodemographic composition of the residing population, other reference populations are needed to properly integrate the samples collected. For the same geographic strata, the number of carsharing members who participated in the recruitment as well as the number of students and employees, whose domicile is in the survey region, for each of the universities involved in the recruitment were obtained.

Precise knowledge of these populations is important because they add certain constraints during the weighting process. For example, it must be ensured that the number of students associated with a certain university reconstituted by the weighted sample does not exceed the number of students registered to that university. The same applies to members of the carsharing and bikesharing services. Detailed knowledge and access to this data is therefore an important issue to be anticipated at the beginning of the process.

For university populations, it has been difficult to obtain accurate data on the type of students. We could not know the number of students by type (full-time or part-time, international students and those away for internships, undergraduate or graduate level). Moreover, the place of residence provided by the universities corresponds to the place where the billing is sent, a place that does not necessarily correspond to the place of residence of the students. This billing location was often in a different region than the one surveyed. For these reasons, it is difficult to know whether the reference populations obtained actually correspond to the target populations or whether they are overestimated. The main method used to expand the results and reconstruct the reference populations is based on the iterative proportional updating (IPU) approach (Ye et al., 2009, Ye et al, 2022). This method allows multiple constraints based on two dependent objects to be considered simultaneously. The objective is to match both object distributions as closely as possible. Usually, this method is used to produce a series of weighting factors that reconstruct both household and people reference populations, while preserving the links between the household and its members. As part of this study, the IPU method is used in a way to reproduce the reference amount of people and households. This method makes it possible to consider simultaneously several constraints based on households and people, but also on other variables such as day of the week, week number, month or number of university students. At the end of the algorithm, the method produces a weighting factor for each of the households in the sample. The process is repeated for all 113 geographic weighting strata.

To reconstruct the reference populations with weighting factors as accurately as possible, several constraints are added. In the context of the 2018 Montreal household survey, the constraints used based on the reference population are the number of households segmented by size, the number of people by gender and age, the number of carsharing members, the number of students for each university and the number of workers for each university.

In addition to these constraints, two more are added regarding the minimum and maximum values for weighting factors to ensure that their distribution follows a lognormal distribution. In addition, the distribution of the sample by day of the week and month are two other constraints added to the methodology. These last two constraints make it possible to correct the temporal variability of the sample according to the day of the week and the month.

All quantities (constraints) mentioned above should be, theoretically, reconstructed using the weighting factor attributed to households. However, the more constraints are used, the more difficult it is to reconstruct the reference populations. In practice, because of the samples, the diversity of constraints and the various parameters used in the IPU, quantities (constraints) are not fully satisfied. A final adjustment is therefore necessary to recreate with more precision the reference populations of the census and/or other sources. This step creates a weighting factor that applies to people. This factor makes it possible to perfectly recreate the reference populations by age groups that are finer than those previously used. Regarding university populations, due to some doubts about the quality and content of the reference populations provided by universities, it was decided to apply a correction only if the reconstituted population exceeded the reference by geographic strata.

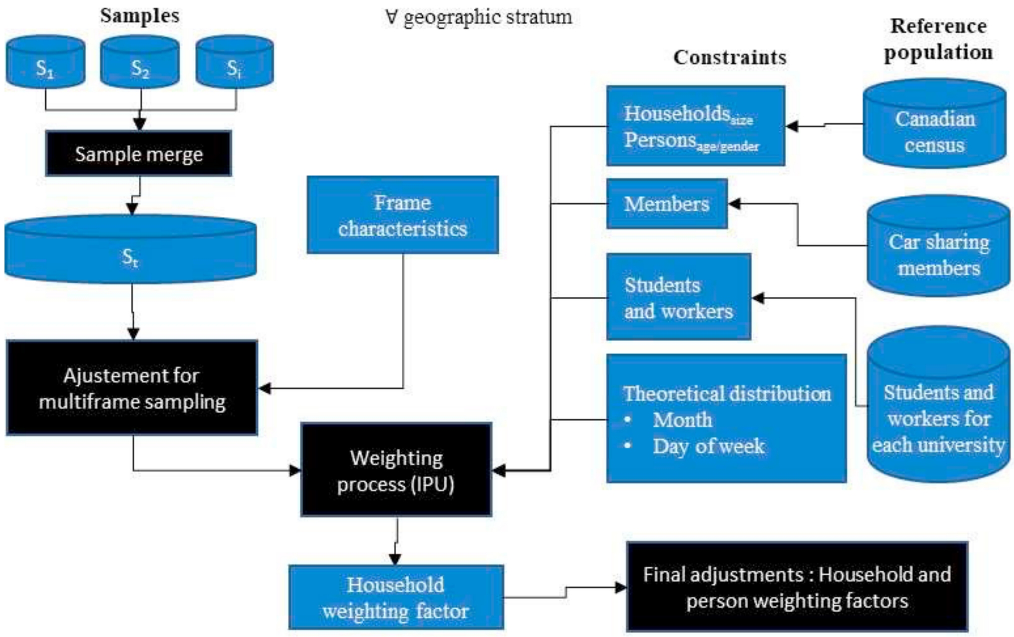

Figure 2 Overall methodological process of sample integration

Figure 2 shows the overall methodology used in the 2018 household survey to combine and integrate the samples. It should be noted that there were no particular constraints or process for the bikesharing member samples given the small sample collected.

5. Results

The methodology makes it possible to obtain weighting factors for the sample of households that tackle the various issues raised previously for the temporal distribution of the sample and the integration of the samples of the multiple sampling frames. Table 5 shows the distribution obtained by considering the weighting factors with respect to the theoretical distribution. The differences are statistically significant compared to the distributions obtained with the unweighted samples that were presented in Table 4.

The distribution according to the day of the week in Table 5 is very similar to the theoretical one where the weighted sample of each day should be 20%. The observed differences between both distributions are statistically significant. For the distribution by month, the weighted distribution is close to the theoretical one without reaching it perfectly and the differences between both distributions are all statistically significant. Nevertheless, the distribution obtained is much closer than the one from the unweighted sample. It should be noted that the correction of these distributions has had a significant impact on certain trip indicators, especially those concerning walking and cycling that are more sensitive to weather conditions in Montreal.

Table 5 Distribution of the weighted sample by day and month

Distribution of sampled households			
		Weight	Objective
Days of week	Monday	20,0%	20,0%
	Tuesday	20,0%	20,0%
	Wednesday	20,1%	20,0%
	Thursday	19,9%	20,0%
	Friday	20,0%	20,0%
Month	September	22,5%	24,4%
	October	28,7%	28,2%
	November	29,1%	28,2%
	December	19,8%	19,2%

It is also interesting to look at the distribution of the weighting factors obtained. Figure 3 shows the distribution of final factors obtained for households and people. Most of the factors obtained are between 10 and 20, which was expected with a sample rate of about 4% of households in the region. However, higher factors are produced, mainly to consider the September adjustment.

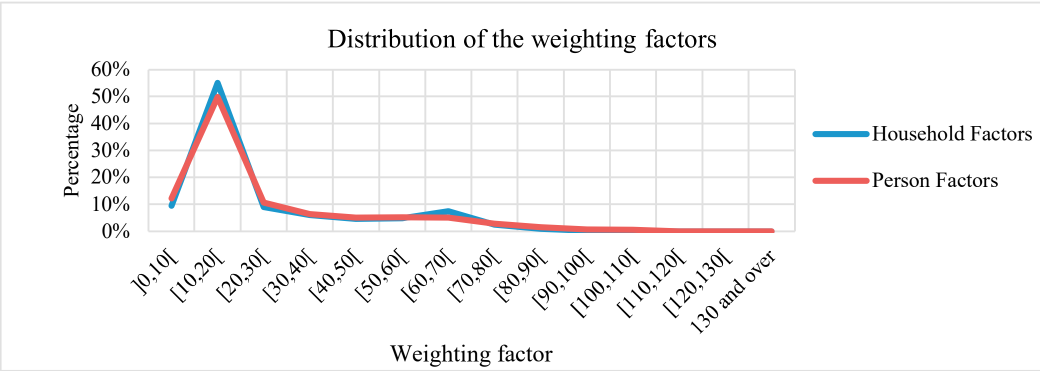

Figure 3 Distribution of the household and person weighting factors

6. Conclusion

The main purpose of this paper was to present the methodology developed as part of the sample integration and weighting from the 2018 household survey in the Montreal region. The elements discussed covered different sampling issues including the use of multiple frames, recruitment at different time periods, and sample integration and weighting. As there is little documentation on methods of integrating and weighting samples at such a scale in transport surveys, the analysis in this paper helps to contribute to this.

The multi-frame methodology used in the 2018 Montreal travel survey raised several issues and challenges related to process and data integration. First, it is important to get the most detailed information about each sampling frame before the survey starts. The knowledge of this information will influence the method that can be used for sample integration afterward. The important information to be obtained should include the number of units in each frame as well as information to determine the membership of each unit in each frame. Obtaining this information becomes more and more complex with the addition of several frames and is sometimes impossible. In addition, this information is not always easy to obtain since some organizations may be reluctant to share it or it may be considered confidential. Subsequently, it is even more important to include questions or mechanisms to determine the membership of every sampled household to all frames. Although this element is simpler, using multiple frames can increase the complexity of the questionnaire, the number of additional questions needed and therefore, the respondent burden.

The number of units of the sampling frames, which can sometimes also serve as reference data in the weighting process, is also important. In addition, it is necessary to be able to assess the quality of the information received. For example, in the context of the 2018 household survey, we had several doubts about the quality of the information received regarding university students because we did not have information on the status of the students (full-time or part-time, etc.) or on the validity of the provided address. Moreover, additional information is needed to adjust or at least validate the results obtained at the end of the process. In the case of the Montreal survey, the percentages of students by age group, the penetration rate of carsharing and bikesharing services, and the number of employees for certain generators are all relevant information that helps improve the sample integration process. Care must be taken to ensure that samples from some frames do not over-represent certain population groups. It is also important to ensure that the information is obtained at a spatial scale compatible with the weighting strata.

In the Montreal survey, the sampling frames covered different time periods. This element added an additional challenge to the data integration process and biased the average autumn weekday. The adjustment included in the weighting method allowed to address this issue. However, it led to an overweight of the samples collected in September, which come mainly from the landline database. This also led to a certain bias in the results. By example, the over-representation of households sampled in September comes from some specific sampling frames and not from the whole. The mobility behaviours of these households, if they are specific to these sampling frames, will therefore be over-represented in the results.

Finally, the proposed methodology also raises questions about the comparability of results with previous surveys. For example, in previous surveys in Montreal, no adjustment of the month had been proposed even though under or oversampling of certain months were observed. However, although the methods are different, this does not necessarily mean that the data are not comparable. Hence, an identical methodology between two surveys does not necessarily mean that the data will be comparable, the response behaviours necessarily vary over time. The objective remains to aim for a most representative sample of the target populations as well as coverage of 100% of these populations.

The geographic stratification used in this study for the weighting process was based on municipal sectors (boroughs or municipalities). The choice of the scale was imposed to us. We have therefore not done an in-depth study on the impact of the choice of geographical strata, although we have compared the results of our methodology at this scale. In general, there was variability in the results for sectors who have small sample size and for sectors with specific population type. For example, some areas near universities benefited more from the addition of certain frames because it allowed them to reach a population that was more difficult to reach with standard frames.

The weighting method used in this study brings together several aspects, all of which have a greater or lesser impact on mobility indicators. The correction of multi-frame sampling is only one of the aspects that is considered in the weighting process. The variability of sampling by day of week and month is another aspect. After studying the impact of the correction factor for multi-frame sampling, we can say generally that the effect of this factor is relatively low on the major mobility indicators at the scale of geographical strata. As can be seen in Table 2, the number of observations that are available in more than two frames is not high for larger samples. For university frames, carsharing or bike sharing), the number of households available in more than 2 frames is higher, but their impact is limited by the size of their samples. This aspect partially explains the low impact of this correction factor for multi-frame sampling. However, the impact of adjusting the distribution of sampling by month had a major impact on several indicators such as modal shares, specifically on public transit, walking and cycling and on certain trip purposes. The study of a sub-population such as university students also reveals significant differences in mobility indicators and in household characteristics for this population. The weighting method was mainly based on the UPI method. Other methods could be tested in the future such as geographically weighted regression.

The methodology presented is not perfect. However, it should not be forgotten that the objective is to get as close as possible to a representative sample of the population. None of the sampling frames used in the 2018 household survey, taken individually, can compose such a sample. It should also be noted that the main objectives of using multiple frames in the Montreal survey were to increase sample sizes and sample behaviours that were not collected with standard frames.

Acknowledgements

The authors wish to acknowledge the Montreal Committee on travel surveys for providing access to the data for research purpose as well as the Mobilité Chair Partners: Ville de Montréal, Société de transport de Montréal (STM), Autorité Régionale de Transport Métropolitain (ARTM), exo and Ministère des Transports du Québec (MTQ). They also want to thank the two anonymous reviewers for their relevant comments. They have contributed to improve the scientific quality of the paper.

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