Principles for addressing urban traffic monitoring challenges

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Abstract

Performance measurement and data-driven decisions are becoming increasingly critical components of transportation departments to help efficiently allocate resources, effectively operate the transportation system, and intelligently plan for the future. Traffic monitoring programs are fundamental for measuring performance and supporting decisions. Traffic data provide ground truth for understanding vehicular movements by mode (e.g., car, bus, truck, bicycle, walking) and serves as the input for executing essential tasks and responsibilities of government agencies. Despite the importance of traffic count data, many jurisdictions have not invested in developing strategies for establishing a robust, adaptable, and sustainable traffic monitoring program.

This position paper provides direction for developing traffic count program strategies based on a best practices review and experience developing traffic count programs in various Canadian jurisdictions. Specifically, it discusses common challenges faced by urban jurisdictions regarding traffic monitoring, illustrates potential implications of insufficient traffic data, and presents a set of guiding principles that jurisdictions can apply to improve their traffic monitoring program. The six principles are responsiveness to need, truth-in-data, consistent practice, base data integrity, data interoperability, and future flexibility. The paper demonstrates the need for a Canadian urban traffic monitoring guide and recommends using the guiding principles as the foundation for this guide.

INTRODUCTION

Performance measurement and data-driven decisions are becoming increasingly critical components of transportation departments to help efficiently allocate resources, effectively operate the transportation system, and intelligently plan for the future. Traffic monitoring programs are critical for supplying these traffic data. Traffic data provide ground truth for understanding vehicular movements by mode (e.g., car, bus, truck, bicycle, walking) and serves as the input for executing essential tasks and responsibilities of government agencies. Despite the importance of traffic data, many urban municipalities have not invested in developing strategies for establishing a robust, adaptable, and sustainable traffic monitoring program.

The recently updated U.S. *Traffic Monitoring Guide* [1] is the foremost document referenced by traffic monitoring practitioners. This guidance is primarily directed at rural traffic monitoring programs which generate the traffic data used to help justify and allocate federal funding to states. Importantly, the *Traffic Monitoring Guide* established consistent and standard methods for producing required statistics, such as traffic volume. However, as this funding model was not extended in the same way to urban municipalities, the focus of the *Traffic Monitoring Guide* has remained rural, leaving specific challenges associated with monitoring traffic in urban areas unaddressed. In Canada, the absence of consistent traffic monitoring guidance for both urban and rural areas has led to the disparate traffic monitoring programs and non-uniform reporting practices that exist across the country today.

The lack of resources and guidance for developing an urban traffic monitoring program is a major reason behind the non-uniform and inconsistent practices of collecting urban traffic data across Canada. The objective of this position paper is to demonstrate that guidance is necessary to assist urban municipalities monitor traffic and to identify fundamental principles that should form the basis of such guidance. The need for guidance is based on the value of traffic data for engineering and planning, the differences between rural and urban traffic monitoring, the challenges these differences present for traffic monitoring, and the insufficient knowledge about how to collect and analyze non-motorized traffic data.

VALUE OF TRAFFIC COUNT DATA

A well-designed traffic monitoring program provides fundamental data for a host of transportation applications and decisions [1]. The breadth of these applications, the multidimensional nature of traffic data types, varying levels of data precision, different temporal orientations, and constantly evolving technological advancements challenge the capabilities and performance of these programs. The following points illustrate these complexities:

- *Breadth of application:* Traffic data support the full spectrum of the transportation engineering functions of a road agency—from planning, to design, operations, maintenance, and management. These functions involve a variety of application contexts, each with their own traffic data requirements. For example, a *planning* study focusing on roadway capacity may require estimates of future total traffic flows on a link-node network. The *design* of road geometry may justify the installation of a raised median at an intersection based on expected increases in the number of pedestrian crossings. Effective *operation* of roads may involve real-time travel delay estimation to inform emergency personnel attending a crash site. The *maintenance* of pavements relies on detailed characterization of truck traffic in terms of axle loads and configurations. Safety and environmental *management* require network based estimates of vehicle-distance travelled to develop relevant performance metrics.

- *Multidimensional nature of traffic data:* As illustrated in the foregoing point, traffic data cannot be considered one-dimensional. Regehr et al. (2009) propose that traffic activity can be described in terms of four primary dimensions (though specific exceptions or additions may exist): volume (the number of movements), weight (truck gross vehicle weight and axle weight), the space occupied by the movement (the length of a truck and its volumetric capacity), and speed. At a secondary level, each of these primary dimensions can be further characterized by vehicle classification (or mode), time, and space/direction. For example, knowledge about traffic volume alone is often insufficient; rather, we typically require further information about traffic volume by vehicle class (e.g., car versus truck), by time (e.g., hourly or monthly variations), and location (e.g., volume entering an intersection or by direction on a segment).

- *Level of precision:* Fundamentally, most traffic detection devices used in traffic monitoring programs measure discrete events—a vehicle or person passes a point and generates a data point. It is seldom sufficient to understand single events; rather, most applications require some level of aggregation in time and/or space. Generally, the planning and management functions require higher levels of data aggregation (less precision) while design, operations, and maintenance rely on finer-grain characterization of traffic events (more precision).

- *Temporal orientation:* Traditionally, traffic monitoring programs have been oriented to provide an understanding of historical traffic activity. Projections of future activity, though measured in similar units such as traffic volume, have typically been generated through demand models. While this distinction remains, new opportunities to integrate these datasets exist because of the similarity between the basic units of measure. In addition, as real-time monitoring technologies evolve, some traffic monitoring programs now also include an ability to measure and respond to real-time events.

- *Technological advancements:* Considerable advances in traffic monitoring technologies have expanded the conventional tools used to observe traffic. Traffic monitoring programs still rely on manual observations, inductive loops, and pneumatic tubes. However, the new repertoire of technologies now includes video detection systems, various non-intrusive wave-based detectors (e.g., infrared, ultrasonic), satellite-based observations, various types of weight monitoring sensors (e.g., quartz sensors, load cells), and on-board tracking devices (e.g., global positioning systems, cell phones). Using on-board tracking devices to collect traffic data is often referred to as “crowdsourcing” and is becoming an increasingly useful source of operational information. While these technologies enable traffic monitoring programs to meet new and growing user needs, they present challenges in terms of calibration and data validation.

These examples demonstrate both the complexity and value of collecting and disseminating reliable traffic data. As no jurisdiction can claim to fully meet their users’ needs, there is a continual need to address these challenges so that appropriate data are used to inform better decisions.

URBAN TRAFFIC MONITORING CHALLENGES

The need to improve traffic monitoring programs in urban areas has long been recognized as users’ needs become increasingly varied [2]. The updated *Traffic Monitoring Guide* [1] responds to many of these demands, but principally focuses on programs run by state agencies rather than urban municipalities. While some challenges are common to rural and urban areas, urban traffic monitoring programs face several unique constraints:

- A variety of organizational units collect traffic data in urban areas; this sometimes leads to uncoordinated collection procedures and an inability to integrate data from disparate sources.
- Interrupted traffic flow in urban areas inhibits the use of certain types of traffic detection technologies, particularly those that rely on sufficient headways and speeds to classify vehicles.
- Dense street networks with multiple access points make it difficult for analysts to assume homogeneity along road segments and compare traffic characteristics between different locations.
- Non-motorized traffic, which has traditionally been under-valued within traffic monitoring programs, is an important indicator of the ability of an urban transportation system to move people. Traffic detection technologies that monitor non-motorized traffic are emerging rapidly.
- The density of the urban street network and fine-grain distribution of land use complicate distinctions between recurrent patterns, anomalous patterns (i.e., resulting from a special event or temporary condition), and erroneous data (i.e., generated from faulty equipment).

These constraints, among others, demonstrate the need for improved guidance for monitoring traffic in urban areas. The principles identified in this paper provide a starting point for the development of more thorough guidance in the future.

IMPLICATIONS OF INSUFFICIENT TRAFFIC DATA

Traffic data form the basis for most transportation engineering and planning decisions and investments. Traffic modeling tools and software and many traffic statistics use traffic volume data in one form or another. Therefore the quality of traffic statistics, traffic models, decisions, and investments are directly affected by data quality. Since little attention has been given to systematically and consistently collecting and analyzing traffic data, excessive or unknown errors in these data are possible. Often municipalities rely on short-duration traffic counts (e.g., peak period intersection turning movement counts, 8-hour counts, etc.) to estimate a daily traffic volume. Expanding these short-duration counts by vehicle type is frequently an onerous task yet accurate and reliable traffic volume estimates by vehicle type are usually a requisite for using engineering tools and applying engineering judgment appropriately.

This part of the paper demonstrates the proportional relationship between traffic volume data and several important equations foundational to traffic safety and transportation engineering planning, design, operation, and maintenance. Specifically, it shows the sensitivity of transportation engineering decisions in terms of traffic data accuracy. Although traffic volume is just one type of traffic data, it is convenient to use this metric to illustrate the importance of traffic monitoring. The following examples illustrate the implications that traffic data quality has on traffic safety, pavement design, and trend analyses.

Traffic Safety Implications

The Highway Safety Manual (HSM) is becoming a standard practice for estimating the number of crashes on the roadway and prioritizing treatments at these locations. The manual develops the concept of safety performance functions (SPFs) which are equations that predict the crash frequency along a road segment or at an intersection. SPFs are developed using detailed crash data from a sample of locations across North America and use annual average daily traffic (AADT) as the primary independent variable. For example, the HSM provides the following SPF for four-leg signalized intersections [3]:

$$N_{spf\ 4SG} = exp\left[-5.13 + 0.60 \times \ln\left(AADT_{maj}\right) + 0.20 \times \ln(AADT_{min})\right]$$

Where:

$N_{spf\ 4SG}$ = SPF estimate of intersection-related predicted average crash frequency for base conditions,
$AADT_{maj}$ = AADT (vehicles per day) on the major road; and
$AADT_{min}$ = AADT (vehicles per day) on the minor road.

Given this equation, the relationship between the predicted crash frequency and AADT is almost directly proportional. Figure 1 demonstrates this relationship and the sensitivity of *N* based on the accuracy of *AADT*. In this figure, the percent error in AADT for both the major and minor approaches is varied from -50 percent to +50 percent. The corresponding error in predicted crash frequency varies from -42 percent to +38 percent.

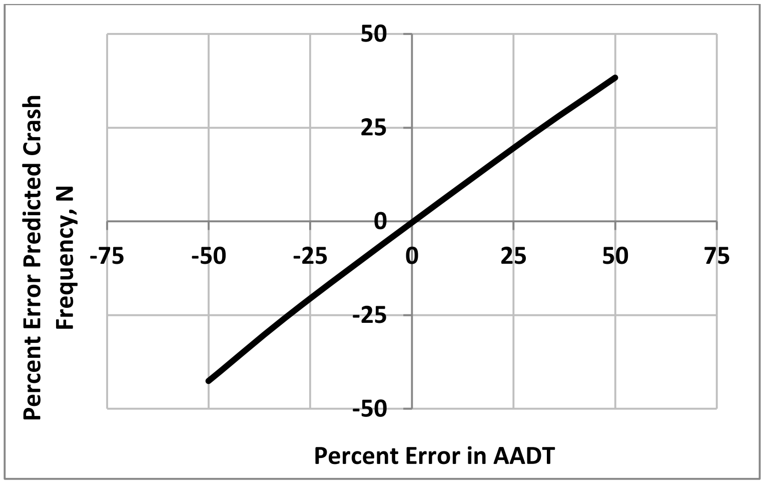


Figure 1: Percent error in AADT as a function of percent error in predicted crash frequency

Using short-duration counts conducted every few years at a site to estimate AADT is prone to error. Experience in various jurisdictions indicates that in some cases this error is greater than 50 percent, in other cases the error is unknown. Both cases are troubling when considering the impact on road safety analyses.

Pavement Design Implications

Emerging practice in the mechanistic-empirical design of pavements relies fundamentally on current and future truck traffic volume by vehicle class, as well as other truck traffic characteristics such as axle load spectra (by axle grouping) and monthly and hourly variations [1]. These requirements challenge traffic monitoring programs in urban areas, which have not traditionally focused on developing detailed characterization of truck traffic. Uncertainty in any of these truck traffic data inputs translates into uncertainty in the design process. To illustrate this point, consider the following situation:

A pavement designer seeks truck traffic data inputs to develop a mechanistic-empirical design of a flexible pavement on a major urban arterial. To start, the designer obtains an estimate of annual average daily truck traffic (AADTT) factored from a short-duration vehicle classification count taken on the arterial. Assume that the short-duration count categorized trucks as either “small” (i.e., non-articulated) or “large” (i.e., articulated). Further assume that reasonable hourly, day-of-week, and monthly factors are available by truck class group (i.e., “small” and “large”) to generate this AADTT. Next, the designer selects a design direction or lane and estimates the percent of trucks traveling in that direction or lane. Then, because different trucks have different axle configurations subject to different load limits, the

AADTT must be disaggregated into ten vehicle classes (from buses to multiple trailer trucks). For each vehicle class, each axle grouping (single, tandem, tridem) must be represented by a distribution of axle loads. These load distributions also change temporally (because commodities and axle load limits may change over the course of a year), so the design requires an estimate of the monthly change of axle load spectra. Ideally, site-specific data support all these estimates and decisions; realistically, the estimates rely on a series of assumptions and therefore carry uncertainty. The final design determines layer thickness based on a series of damage models, some of which are also uncertain.

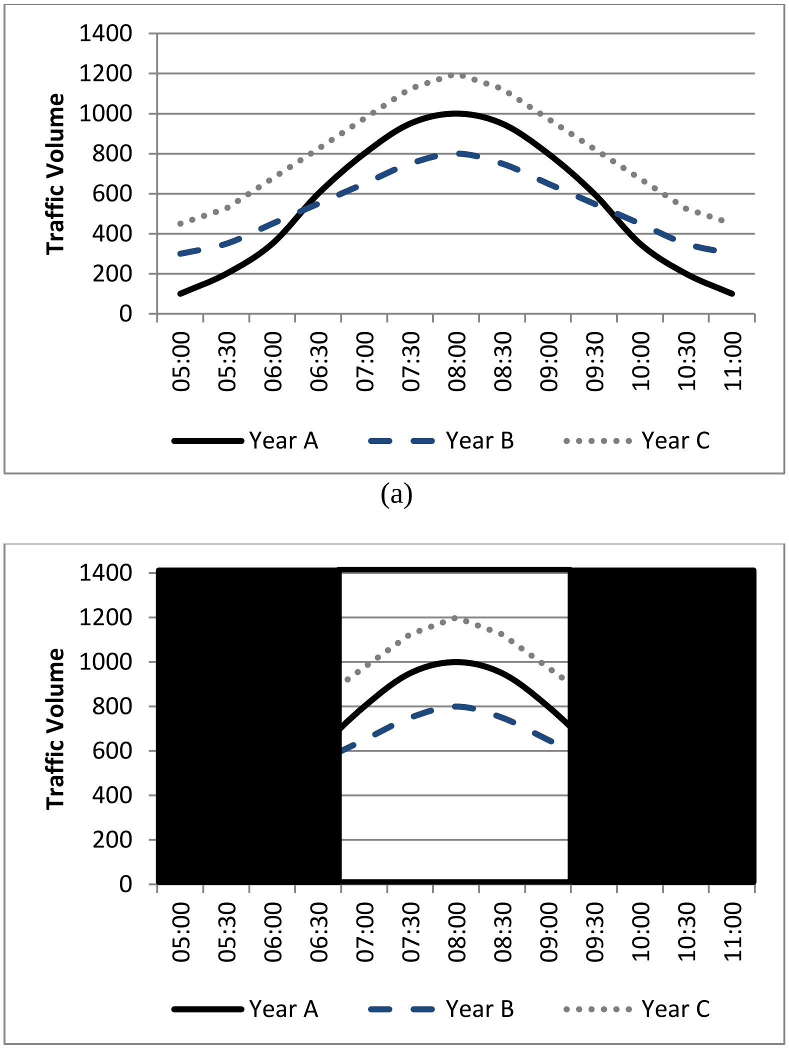
The literature indicates that uncertainty or error in truck traffic data (particularly axle load spectra) have significant impacts on pavement design [4, 5]. Given the paucity of truck traffic data in urban areas, urban jurisdictions will likely need to rely on their provincial (or state) counterparts to provide truck traffic data (if available) that they can reasonably apply for pavement design purposes. Knowing that urban areas typically experience different types of truck traffic movements (e.g., vehicle classifications, temporal variations), there is a need for more robust urban truck traffic monitoring programs to help verify the reasonableness of using data generated in rural areas.

Trend Analysis

Trend analyses also require accurate traffic data since trends are often computed using historical data and sometimes projected decades into the future. Even small errors in historical data can be magnified when projected this far into the future. While this can have implications for long-term transportation planning, two other important and somewhat emerging areas where accurate traffic data are necessary are calculating mode split and identifying peak period spreading.

Mode split is not necessarily an emerging area; however, there has been an increasing emphasis on calculating pedestrian and bicyclist volumes as part of the mode share, typically measured as vehicle-kilometres travelled (VKT). Non-motorized traffic monitoring programs, especially when compared to motorized vehicle traffic monitoring programs, are undeveloped and therefore tend to produce lower quality traffic data. This introduces difficulty in calculating mode share and also casts doubt when comparing VKT estimates produced from such different data sources. An urban traffic monitoring guide that can address this issue and recommend methods for minimizing the effects of these differences would be a valuable tool.

Peak period spreading occurs when commuters leave earlier or later than the current AM and PM peak periods in an effort to avoid congestion. Figure 2a illustrates the theoretical change in traffic volumes and temporal distribution of this phenomenon. In Year A there is a fairly typical AM peak period. In Year B, the total traffic volume between 05:00 and 11:00 does not change; however, commuters leave both earlier and later in the morning. In this example, this increases traffic volumes at the edges of the peak but decreases the magnitude of the peak at 08:00. In Year C the total traffic volume has increased by 50 percent from Year B; however, the temporal distribution has remained the same. The issues faced by the transportation and traffic engineer are different in each scenario presented. Figure 2b shows the same traffic volume and distribution as Figure 2a. However, it illustrates what the traffic data analyst would observe if traffic data were only collected during the traditional peak period (e.g., perhaps a count beginning at 07:00 and ending at 09:30). Based on these data it would not be unreasonable to conclude that peak period traffic was declining from Year A to Year B. Since these data do not capture the whole story at this location, this conclusion would not capture the peak spreading that is occurring and it would fail to recognize that traffic volumes have not decreased but rather shifted earlier and later. Consequently, it would be difficult to anticipate the traffic volumes experienced in Year C without knowing that the apparent decrease from Year A to Year B was not a decrease after all. Between Year A and Year C it would be possible based on these data to implement inappropriate traffic operations measures and fail to properly plan and invest for the future. This example simplifies a complex situation but it is not difficult to extend the theoretical underpinnings of this situation to others experienced in urban areas.



(a)

(b)

Figure 2: Peak period spreading

GUIDING PRINCIPLES TO ADDRESS URBAN TRAFFIC MONITORING PROGRAM CHALLENGES

The previous sections described the challenges concerning urban traffic data collection and implications that these challenges can have on transportation engineers and planners. These challenges support the need for providing guidance to urban municipalities for traffic monitoring. This section describes six guiding principles as shown in Table 1 which should be used as the foundation for guiding traffic monitoring in Canadian urban areas and which can be applied to address current challenges. As each principle is described, it will become apparent that they are not necessarily mutually exclusive and that it is often difficult to follow one principle without applying another.

Table 1: Principles of traffic monitoring [6, 7, 8]

Principle	Objective
Responsiveness to needs	Supply users with required data, in a timely manner and in the format preferred; handle requests for information quickly; provide the most up-to-date information.
Truth-in-data	Disclose the methods and technologies used; provide estimates of the accuracy of all statistics; document and disclose methods used for data sampling and expansion.
Consistent practice	Adopt standard methods or encourage standards to be established; conform to standard practice.
Base data integrity	Screen raw data for errors and anomalies; the raw data may be accepted or rejected but not adjusted or imputed.
Data interoperability	Data should be shared with other jurisdictions and collection efforts coordinated; the traffic information system must link to other databases.
Future flexibility	The system should be flexible and modular to accommodate new technologies and new methods.

Responsiveness to need

This principle ensures that a traffic monitoring program understands data user needs and maximizes its resources to provide necessary data. This can be achieved by surveying known data users (e.g., city staff, consultants) and identifying best practices and data uses from other jurisdictions. Data providers are sometimes unaware of who is using their data and how data are being used, especially cities providing open source data. Conversely, data users may not know how data are collected or the type of data that could reasonably be collected. Maintaining open communication between data providers and users can help ensure that this principle is followed. Establishing a local data user's forum is one way to facilitate this communication and interaction. At a minimum these types of forums should be organized every five years [1].

Truth-in-data

Truth-in-data is the primary principle on which traffic monitoring guidance is based [6]. It refers to the documentation and disclosure of the procedures used to collect, analyze, and summarize traffic data [9]. This documentation can include descriptions of the data collection technologies used, the method used to collect data (e.g., duration of counts), data type collected, quality control and assurance measures applied, assumptions implied in the calculation of traffic statistics, and so forth. Another type of documentation that is critical for traffic monitoring is metadata. In the context of traffic monitoring, this refers to data about traffic data. Without metadata, traffic data are essentially worthless since there is no way for the data user to assess its quality, understand its limitations, and use it appropriately. Calculating traffic statistics and basing decisions on data without metadata can lead to misguided conclusions and decisions. Ultimately a traffic monitoring program manual should be created for each jurisdiction which includes this documentation.

Standard procedures for creating metadata are available (e.g., ASTM E2468-05 Standard Practices for Metadata to Support Archived Data Management Systems; ISO 14817 Transport Information and Control Systems – Requirements for an ITS Central Data Registry and ITS/TICS Data Dictionaries; and INCITS/ISO/IEC 9075 Information Technology – Database Languages-SQL 2003). Examples, albeit few, of metadata to consider include:

- Data completeness – percent of records with valid and present values
- Data coverage – percent of centre-line kilometres with count coverage
- Positional accuracy – degree of horizontal and vertical control in the coordinate system
- Data file format – file extension and compatibility with software
- Timeliness – represents the degree to which data values are up to date
- Data origin – which agency collected the data

Consistent practice

This principle ensures that the traffic monitoring program is executed consistently and follows a standardized procedure for collecting, analyzing, and disseminating traffic data. Examples of standardizing the data collection program include developing a traffic count schedule whereby traffic data are collected at specific locations on a regular basis, defining the type of data that are collected and how these data are collected, and defining a specific set of vehicle types. Examples of standardizing data analysis procedures include following a consistent procedure for conducting quality control and assurance measures and applying consistent assumptions and calculations when producing traffic statistics. Following and documenting consistent practices promotes transparency in the program and allows staff or external reviewers of the program to assess its performance.

The upcoming Transportation Association of Canada publication titled Changing Practices in Data Collection on the Movement of People, the AASHTO Guidelines for Traffic Data Programs [10], the American Society for Testing and Materials, and the FHWA Traffic Monitoring Guide [1] each provide information that municipalities could find useful for instilling consistent practices in their traffic monitoring program.

Base data integrity

This principle requires that traffic data must be retained without modification or adjustment. In essence, raw traffic data can either be accepted or rejected. Anomalous data should not be adjusted or “fixed” to make it “more acceptable.” Further, anomalous data should not be rejected simply because it does not match historical records or trends. Jurisdictions often apply different methods for interpolating missing data and use different criteria for testing data validity. Following the consistent practice principle, a standard method for treating missing and invalid data is necessary.

Anomalous data can still be valid data; it is up to the transportation professional and the quality control and assurance methods to determine if it is or not. Following the base data integrity principle requires the application of the truth-in-data principle. If anomalous data are retained, the data user must understand why data are considered valid and how to use these data. This principle allows data to “speak for itself” and when combined with metadata provides the transportation professional with the support necessary to confidently use and disseminate these data. Ensuring base data integrity builds trust with data users and credibility of the traffic monitoring program.

Data interoperability

The value of data can be increased substantially by integrating it with other data sources. The data interoperability principle encourages data to be collected and converted into compatible file formats along with common fields that facilitate linking between disparate databases. Horizontal integration of data can occur across modes when motorized traffic data are combined with non-motorized traffic data. This type of interoperability facilitates the calculation of mode share among many other capabilities and calculations. Horizontal data interoperability can also occur between jurisdictions which can reduce data collection efforts and costs. Vertical integration of data can occur across disciplines and between traffic and non-traffic related databases. For example, using data interoperability and applying data linking procedures to integrate infrastructure data, traffic data, collision data, and medical data can determine the cause and effect of a collision, including its total cost to the public [11]. An important element in data interoperability is the capability of relating data, which can occur by directly linking a common discriminant variable or by establishing spatial and temporal data linkages. For example, each observed traffic event should be characterised by a unique geographic coordinate and time stamp to facilitate data linkage.

Future flexibility

Traffic data needs and the technologies available to collect data are constantly changing. In the case of technologies, these changes are occurring rapidly. If a traffic monitoring program does not follow the principle of future flexibility, it risks becoming obsolete or inadequate. Examples of the type of flexibility required includes the ability to integrate new types of data into the program, the capability of using different software and tools for analyzing data, and seamlessly adopting new data collection technologies. From this perspective, agencies should dissociate themselves as much as possible from individual vendors of traffic data collection technologies and data management software. Although there are benefits from committing to a single vendor such as reduced costs and familiarity, these benefits should be weighed against the potential risk to future flexibility.

Public agencies do not have the resources to develop in-house traffic data collection technologies such as inductive loops and rely on vendors to supply these services. However, many public agencies do have the resources to manage and analyze traffic data. Therefore, in-house traffic data management programs could be a feasible approach for maintaining future flexibility. Again, the benefits of an in-house versus vendor-based data management solution must be weighed.

The principle of future flexibility can sometimes conflict with the principle of consistent practice since new technologies can demand new approaches and methods for monitoring traffic. These new methods can sometimes render historical comparisons impossible. However, traffic monitoring programs should not resist change based solely on maintaining the ability to conduct time-series analysis. Nonetheless, the decision to embrace new technologies at the risk of interrupting time-series analyses should be carefully considered.

CONCLUSION

Traffic data are a fundamental input for most transportation engineering decisions and investments. There is currently insufficient guidance for consistently collecting urban traffic data and consequently, the quality of these data is often poor or unknown. The U.S. Federal Highway Administration has developed and updated the *Traffic Monitoring Guide* which is considered by many to be the best practice in collecting and analyzing traffic data. However, this guide is primarily for highways in rural areas and has been developed with U.S. needs in mind. A similar guide for Canadian urban areas does not exist.

This paper identifies challenges that many urban traffic monitoring programs face, uses examples of traffic data applications such as road safety, infrastructure design and maintenance, and trend analysis to demonstrate the implication of making engineering decisions without addressing these challenges, and presents a set of guiding principles that jurisdictions can apply to improve their traffic monitoring program. The six principles are responsiveness to need, truth-in-data, consistent practice, base data integrity, data interoperability, and future flexibility. The paper demonstrates the need to provide guidance for traffic monitoring in Canadian urban areas and recommends using the guiding principles as the foundation for this guidance.

Applying the guiding principles is a good start for improving urban traffic monitoring. There are still many specific challenges to be addressed which require additional research. Examples include developing methods for collecting bicycle and pedestrian data, determining if non-motorized traffic pattern groups can be created as they are for motorized traffic in rural areas, establishing standard procedures for analyzing bicycle and pedestrian data in terms of calculating annual average daily volumes or performing quality control and assurance measures, understanding how to integrate emerging passive traffic count technologies (e.g., Bluetooth) with active traffic count technologies (e.g., inductive loops), and developing methods for collecting truck traffic data in terms of truck classification and weight.

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