**Title**

Understanding How cities can link smart mobility priorities through data



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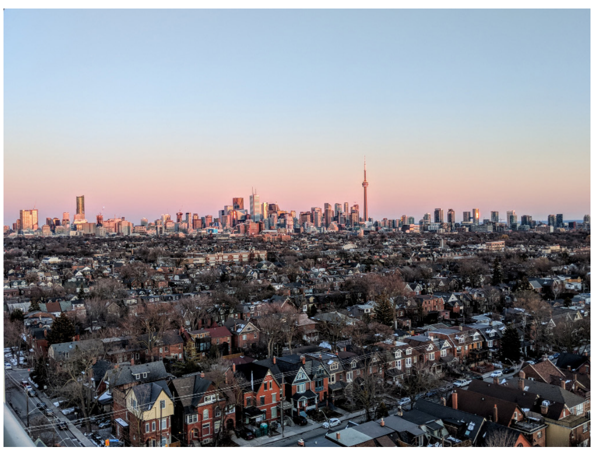
# UNDERSTANDING HOW CITIES CAN LINK SMART MOBILITY PRIORITIES THROUGH DATA





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## 1. Introduction

The 21st century is beginning to deliver on some of the futuristic expectations that modern society has had for transportation throughout much of the post-war era. Cities are starting to become smarter, using data, sensing, and advanced communications to improve the lives of citizens. Vehicles are in the early stages of becoming truly automated, with potential benefits spanning mobility, accessibility, safety, and the environment. At the same time, electric drivetrain vehicles are growing in market share and decreasing in cost, yielding benefits for urban air quality and energy security. Indeed, there are encouraging signs that these developments will alleviate some current stresses on the transportation systems, though if cities do not proactively manage the implementation of these efforts, innovative mobility technologies could result in widespread traffic congestion, degraded air quality, and a deterioration in the overall quality of life for most citizens. Clearly, there is a long way to go in the development and proliferation of these technologies before they become common and widespread. But that future is now on a visible horizon.

A central component and facilitator of this future is data, which is essential to provide an evidence-based approach for cities to measure the impacts from the new technologies that will enable smarter cities. These impact categories span a number of areas. For the purposes of this white paper, we focus on 1) safety, 2) transportation, 3) equity, 4) environment, 5) energy, and 6) congestion.

Despite the importance of evaluating impacts over time, data limitations exist today and may continue to persist tomorrow in ways that hinder the ability of cities to effectively measure and monitor the performance of innovative technologies in achieving their intended aims. A first step toward addressing these limitations is to better understand the inventory of data needs and gaps that persist in the current environment for smart city innovations that are likely to exist in the near future. Completing an inventory of all possible future scenarios would be almost impossible, but it is feasible to identify near-term gaps that exist through an evaluation of data needs required for measuring project impacts that have been advanced within the scope of smart city deployments and public transit integration of advanced technologies.

This white paper presents a generalized evaluation framework that can be used for assessing project impacts within the context of transportation-related city projects. In support of this framework, we discuss a selection of metrics and data sources that are needed to evaluate the performance of smart city innovations. We first present a collection of projects and applications from near-term smart city concepts or actual pilot projects underway (i.e., Smart City Challenge, Federal Transit Administration (FTA) Mobility on Demand (MOD) Sandbox, and other pilot projects operating in the regions of Los Angeles, Portland, and San Francisco). These projects are identified and explained in Section 2 of this report. Using these projects as the basis for hypothetical case studies, we present selected metrics that would be necessary to evaluate and monitor the performance of such innovations over time. We then identify the data needs to compute those metrics and further highlight the gaps in known data resources that should be covered to enable their computation. The objective of this effort is to help guide future city planners, policy makers, and practitioners in understanding the design of key metrics and data needs at the outset of a project to better facilitate the establishment of rigorous and thoughtful data collection requirements.

## 2. The Smart City Challenge and Federal Transit Administration Mobility on Demand Sandbox Projects

As technological advances are made within intelligent transportation systems (ITS) applications, there is great potential to use these technologies to address the changing needs and travel patterns of cities. In December 2015, the United States Department of Transportation (US DOT) launched the Smart City Challenge as an initiative to explore the potential capabilities of incorporating these technologies into urban areas throughout the country. The vision of the challenge was to demonstrate how integrated data, ITS, and other innovative applications could improve safety, enhance mobility, and address climate change across a range of different cities with varying landscapes, density, and infrastructure.

In total, 78 cities submitted proposals to the Smart City Challenge. Of those, seven were picked as finalist cities, consisting of: Austin, Columbus, Denver, Kansas City, Pittsburgh, Portland, and San Francisco. These finalists were then asked to develop more comprehensive plans for deploying smart-city applications to solve key problems facing their city. While there could only be one winner (Columbus), the seven fully developed applications serve as a foundational resource for defining the set of projects that these cities saw as near-term initiatives that could advance their broader smart-city vision. Table 1, shown on the following page, provides an overview of the projects proposed by the seven finalist cities (see Bibliography). The initial metric definitions covered all of these projects. Following the initial definition phase, specific data resources for metric development as well as data gaps were explored for a subset of these projects (consisting of Portland and San Francisco). The projects within this subset are identified in bold within Table 1 below.

**Table 1 Overview of Smart City Finalist Projects**

| Region | Project | Description |
|---|---|---|
| Austin | Automated and Connected Vehicles | Conduct a series of automated vehicle pilots, including downtown circular shuttles and airport shuttles. |
| | Fleet Electrification | Convert non-electric mass transit and private sector vehicle fleets to electric. |
| | Mobility Marketplace | Release a new multimodal app that allows users to route, book, and pay for trips. |
| | Sensor Systems | Improve upon existing sensor and ITS technologies to better detect and forecast traffic conditions. |
| | Smart Stations | Establish park-and-ride stations to facilitate travel from the suburbs to downtown. These stations will provide access to bus rapid transit, rail transit, bikesharing, carsharing, and automated vehicles. |
| Columbus | Access to Employment | Establish automated circular shuttles to support job access. |
| | Connected Visitors and Residents | Improve access to real-time information regarding events, public transit, traffic, and parking. |
| | Electrification and Sustainable Transportation | Reduce greenhouse gas (GHG) emissions by integrating alternative propulsion technologies, including fleet electrification, and expanding charging infrastructure. |
| | Mobility Marketplace | Establish smart passes to pay for multimodal travel. This will be in the form of a smartphone app or smart card. |
| | Smart Logistics | Improve goods movement through real-time data describing traffic and weather and enhanced routing for freight trucks. |
| Denver | Data Management and First/Last Mile Connection | Establish partnerships between the public and private sector to facilitate first/last mile connections through ridesourcing and build a shared data platform. |
| | Electrification and Sustainable Transportation | Convert vehicle fleets to electric and expand charging infrastructure. |
| | Mobility on Demand | Release an updated version of an existing multimodal app. The new version will incorporate ridesourcing and allow users to reserve and estimate the cost of multimodal travel and parking. |
| Kansas City | Connecting People through Infrastructure and Information Technology Integration | Expand the existing street car line and build additional interactive kiosks that provide WiFi, wayfinding, and other traveler information services. |
| | Economic Development | Establish bus rapid transit lines to support job access. |
| | Enhanced Mobility | Conduct a series of automated and connected vehicle pilots, including shuttle systems that operate downtown and go to and from the airport. The project will also support fleet electrification. |
| Pittsburgh | Open Platforms | Build an open data platform to encourage data sharing and support mobility innovations. |
| | Smart Spines and Adaptive Transportation Systems | Establish transportation corridors that prioritize public transit and freight and facilitate automated vehicle movement. This will include sensor and ITS technologies to collect and report real-time traffic data. |
| **Portland** | **Connected Vehicles** | **Conduct a connected vehicle pilot that incorporates TriMet buses and local carsharing fleets.** |

**Table 1 Overview of Smart City Finalist Projects (continued)**

| Region | Project | Description |
|---|---|---|
| Portland | EV Charging Infrastructure | Repurpose street lights and parking meters into multi-purpose vehicle charging stations. |
| | Multimodal Application and Data Marketplace | Release a new multimodal app that allows users to route, book, and pay for trips. The app will incorporate options for private and shared mobility, including ridesourcing and carsharing. |
| | Traffic Management | Implement connected vehicle technologies at selected intersections to slow traffic flow and help avoid collisions. |
| San Francisco | Data Collection and Data Sharing | Build a shared data platform comprised of information from sensors, smartphone apps, and private companies to support current and future mobility innovations. |
| | Shared, Electric, Connected, and Automated (SECA) Vehicles | Implement a multi-phased approach to deploy SECA vehicles. This will include a shared data platform, a trip planning app, and a framework to manage rights-of-way to curb space and traffic lanes, among many other features. |

In addition to the Smart City Challenge, the Federal Transit Administration (FTA) launched its own initiative to explore how public transit agencies could incorporate new technologies that complement and support the traditional functions of public transit. This initiative, called the Mobility on Demand (MOD) Sandbox Program, is part of US DOT's research agenda, and will demonstrate the potential of MOD services. In total, the MOD Sandbox Program involves 11 different pilot projects throughout the country. These projects will demonstrate different MOD concepts and solutions to be executed through local partnerships. Ultimately, the evaluation of each project's benefits and impacts will guide the future implementation of MOD services within transportation networks throughout the country.

Because of the forward-thinking nature of the MOD Sandbox Program, it too serves as a resource for defining advanced applications that may see near-term implementation within cities. The MOD Sandbox Program includes a variety of projects within Arizona, California, Florida, Illinois, Oregon, Texas, Vermont, and Washington State. As with the Smart City Challenge, all of these projects were explored for developing metric definitions within the subject areas of interest. Table 2 provides an overview of these projects (see Bibliography). The smaller subset of projects that we focused on in the subsequent stages of this research (i.e., data source and gap identification) are outlined in bold within the table (consisting of Los Angeles, Portland, and San Francisco).

**Table 2 Overview of MOD Sandbox Projects**

| Region | Project | Description |
|---|---|---|
| Chicago | Incorporation of Bike Sharing Company Divvy | Release an updated version of Chicago Transit Authority's (CTA) existing trip planning app. The new version will incorporate Divvy, a biksharing service, and allow users to reserve and pay for bikes within the app. |
| Dallas | Integration of Ride-Sharing into GoPass Ticketing Application | Release an updated version of Dallas Area Rapid Transit's (DART) existing trip planning app. The new version will incorporate ridesharing services to provide first/last mile connections to transit stations and allow users to pay for services within the app. |
| **Los Angeles** | **Two-Region Mobility on Demand** | **Establish a partnership between Via and LA Metro. Via will provide first/last mile connections for passengers going to or leaving from transit stations. There is a companion project that will take place in Seattle.** |
| Phoenix | Smart Phone Mobility Platform | Release an updated version of Valley Metro's existing trip planning app. The new version will incorporate a variety of mobility options, including ridesourcing, bikesharing, and carsharing, and allow users to pay for services within the app. |
| Pinellas County (Florida) | Paratransit Mobility on Demand | Improve paratransit service by combining services from taxi, carsharing, and traditional paratransit companies. |
| **Portland** | **Open Trip Planner Share Use Mobility** | **Release an updated version of TriMet's existing multimodal app. The new version will provide more sophisticated functionality and features, including options for shared mobility.** |
| **San Francisco Bay Area** | **Bay Area Fair Value Commuting** | **Reduce single-occupant vehicle (SOV) use within the Bay Area through commuter trip reduction software, a multimodal app, workplace parking rebates, and first/last mile connections in areas with poor access to transit.** |
| | **Integrated Carpool to Transit** | **Establish a partnership between Scoop and Bay Area Rapid Transit (BART). Scoop will match carpoolers and facilitate carpooling trips for passengers going to or leaving from BART stations with guaranteed parking.** |
| Tacoma | Limited Access Connections | Establish partnerships between local ridesharing companies and Pierce Transit. The ridesharing companies will provide first/last miles connections to transit stations and park-and-ride lots with guaranteed rides home. |
| Tucson | Adaptive Mobility with Reliability and Efficiency | Build an integrated data platform that incorporates ridesharing and carpooling services to support first/last mile connections and reduce congestion. |
| Vermont | Statewide Transit Trip Planner | Release a new multimodal app for VTrans that will employ both fixed and flexible (non-fixed) modes of transportation to route trips in cities as well as rural areas. |

In addition to the projects bolded in Tables 1 and 2, Table 3 includes additional projects beyond the Smart City Challenge and MOD Sandbox in Los Angeles, Portland, and San Francisco (see Bibliography).

**Table 3 Overview of Additional Pilot Projects Specific to Three Regions**

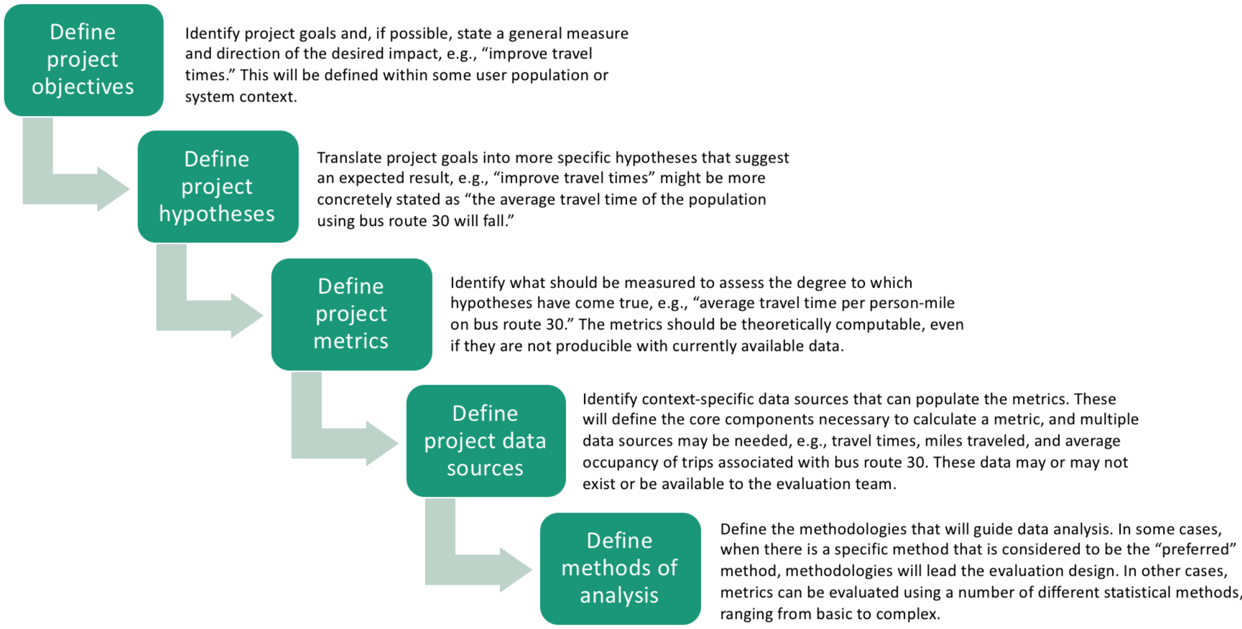
| Region | Project | Description |
|---|---|---|
| Los Angeles | Electric Carsharing | Deploy 100 battery electric vehicles into the BlueLA carsharing program located in disadvantaged communities. |
| | Microtransit | Design and test a demand-responsive service that complements transit to improve mobility, customer experience, and system performance through a partnership with LA Metro. |
| Portland | Administrative Rules for Ridesourcing | Establish a robust regulatory structure over ridesourcing companies. |
| | Electric Carsharing | Deploy used electric vehicles to enhance zero-emission mobility access to underserved residents in the Hacienda community. |
| San Francisco | Connected Carpool | Transform existing traffic lanes into high occupancy vehicle (HOV) lanes to encourage commuter carpooling. |
| | Dynamic Curbs | Allocate curb space to ridesourcing vehicles for passenger pick-up and drop-off. |
| | On-Street Vehicle Sharing Permit Program | Establish city parking spaces for carsharing vehicles. |
| | Private Transit Vehicles Permit Program | Establish a set of regulatory rules for private transit vehicles. |

We identified metrics that would be useful for measurement across the impact categories referenced earlier. These metric definitions are among those that can quantify project performance. Not surprisingly, the list of metrics identified is not exhaustive, as new metrics can be constructed to serve unique purposes. However, given that these metrics are identified across a broad range of impact categories, they require a review of a number of potential data sources that can support their calculation and tracking. The structure of these impact categories and metrics, as well as the data sources that could support them, are discussed in the sections that follow.

## 3. Structure of Evaluation Framework and Metrics

With the evaluation of any project, there can be utility in establishing an evaluation framework, which can help to guide the formulation of questions, define metrics for measurement, and identify data sources. An evaluation framework is especially useful when a project assessment addresses a number of diverse questions. Before detailing project metrics and supporting data sources, we provide a high-level evaluation framework, which could be applied to the projects listed in this paper. This framework could be applied to project evaluations similar to the pilots proposed in the Smart City Challenge and MOD Sandbox, as well as other transportation-related city projects that impact transportation systems in multiple ways. The following figure outlines five steps which serve as a generalized process that can be applied to evaluate a project:

**Figure 1 Overview of Five Key Steps in Evaluation Framework**




We describe each step in more detail below.

1. Define project objectives: Defining the project objectives is usually a straightforward process, but it can force a project team to clarify what a project can and cannot do realistically. Project goals may simply be to "improve safety," "improve travel times," "increase accessibility," "reduce emissions," "improve information quality," or "reduce user or system cost," as defined within some user population or system context. Many (but not all) project goals in transportation will state a general measure and direction of the desired impact. But there are exceptions to this, which may constitute overall goals but do not prescribe the impact of something that can be measured.

2. Define project hypotheses: It is helpful to translate project goals into statements that offer some concrete definition as to what is being measured and the expected outcome. Hypotheses are declarative statements that suggest what is expected to be the result of a project objective. For example, the objective of "improve travel times" might be more concretely stated as: "the average travel time of the population using bus route 30 will fall when using this bus route." In this statement, the hypothesis offers a defined population (those using bus route 30), a metric (travel time), and a direction of expected change for that metric (decrease). This hypothesis can be useful for drawing boundaries around what is and is not considered part of the measurement. Lastly, hypotheses may be stated in terms that would suggest the production of a "yes/no" answer, but in reality, many impacts occur in distributions, with asymmetric (or non-homogeneous) impacts across the population. That is, for innovations/pilots, some people will

experience the expected decreased travel times, while others experience no change, and still others may experience undesirable travel time increases. The hypotheses should encourage the evaluation to capture this nuance or distribution of impacts.

3. Define project metrics: Once the objectives and hypotheses have been defined, it is useful to define what should be measured to assess the degree to which those objectives have been met. However, key questions must be addressed here as to what are the appropriate types of measures that should be applied. This is the step that translates "reduce emissions" to "lower the emissions per person-mile from ridesourcing/transportation network company (TNC) vehicles," for example. The initial metrics defined should be at least theoretically computable, even if they are not necessarily producible with currently available data. The process of establishing desired metrics is useful because it helps to reveal data gaps that may be addressable through future research or improved data collection efforts.

4. Define project data sources: With metrics defined, the next step is to define data sources that can populate those metrics. Available data are context specific. Data that may technically exist may not be available to the project or evaluation team. The data define the core components that are used to calculate a single metric, and multiple data sources may be needed. For example, the single metric of "emissions per person-mile from ridesourcing/ TNC vehicles" requires several data sources. One of those data sources is vehicle fuel efficiency, while a second is the total number of miles traveled. A third is the average occupancy. The second and third data are numbers hard to produce in the present day and usually are not publicly available or continuously measured. In such instances, the assessment of available data sources can require cycling back to the definition of metrics, where metrics need to be revised or qualified to address a limitation in data availability. When data limitations are encountered, another option is to consider the use of alternative data collection methods or proxies. For example, we could approximate ridesourcing/TNC vehicle occupancy based on reported national averages, trends, or surveys. This information could be useful to project planners in the event that comprehensive data are unavailable.

5. Define methods of analysis: At some stage in the course of implementing an evaluation, it is necessary to define the methodologies that will guide data analysis. Methodologies can sometimes lead the evaluation design when a specific method is considered to be the "preferred" method. For example, the analysis of transportation modal choice using a choice model will require a specific data design that will influence the metrics and process. In other cases, well designed metrics of performance can be evaluated using a number of different statistical methods, from basic to complex. We note here that advanced models or statistical analyses are not always required to answer important questions; certain metrics can be evaluated by simply aggregating or plotting data to find averages or basic trends. The evaluation framework needs to consider the analytical methods that can be applied to the data design during steps 2 through 4. However, locking in on a single method too early in the process can cause an evaluation to overlook potentially simpler ways to address the core questions of

interest. This is a subjective and case-specific process, and so there should not be a rule as to when the method is defined. Methods of evaluation are important for consideration within a framework, and the most robust metric and data designs (those that are flexible to answer many different questions at different scales of aggregation) will be able to use a variety of methods to address the same question.

The discussion that follows supports this white paper's primary goal of exploring metrics that can support the application of this framework to evaluating impacts from projects like those proposed by the Smart City and MOD initiatives. For review, the impact categories that we explore include:

1. Safety
2. Transportation
3. Equity
4. Environment
5. Energy
6. Congestion.

We formulated metric examples to quantify project impacts across these six focus areas. In total, we established metric definitions for every project listed in Tables 1 to 3 and grouped them into one of these six impact categories. As one might expect, there is considerable repetition among the metrics and six impact categories with overlapping themes among many of the pilot projects. To avoid repetition, we list the complete set of metric definitions for one illustrative project, San Francisco's Smart City initiative focusing on Shared, Electric, Connected, and Automated (SECA) vehicles (see Bibliography). We chose this project to exemplify metric definitions because it covers a wide range of impacts and demonstrates the different types of metrics for each impact category.

**Table 4 Metric Definitions Across Key Impact Categories for San Francisco's Proposed SECA Vehicle Project (with additional metric examples)**

| | |
|---|---|
| **Safety** | Number of SECA vehicle collisions<br>Vehicle miles traveled (VMT) with SECA vehicles<br>Number of injury collisions and fatalities with SECA vehicles<br>Injury and fatality rate of SECA vehicles (per mile)<br>Injury and fatality rate of non-SECA vehicles (per mile) |
| **Transportation** | Unlinked trips with SECA vehicles<br>Passenger miles traveled (PMT) with SECA vehicles<br>VMT with SECA vehicles<br>Average occupancy of SECA vehicles<br>Parking utilization by location<br>**Additional examples include:**<br>Travel mode share before and after project implementation<br>Average passenger wait time<br>Average trip time<br>Average trip distance |
| **Equity** | Demographic profile of vehicle owners<br>Demographic profile of users<br>Spatial distribution of locations served<br>Demographic distribution of areas served<br>**Additional examples include:**<br>Average trip cost per mile |
| **Environment** | Fuel efficiency of SECA vehicles<br>Emissions per mile of SECA vehicles<br>Emissions impact from change in behavior as a result of the project |
| **Energy** | Fuel efficiency of SECA vehicles<br>Energy consumption per mile of SECA vehicles (kWh)<br>Energy impact from change in behavior as a result of the project |
| **Congestion** | Average speed between origins and destinations<br>Spatial density of vehicles<br>Hours per day SECA vehicles are moving on the road<br>Distribution of VMT per hour<br>Count of vehicles driving per hour<br>**Additional examples include:**<br>Number of SOV trips avoided by time and by origin/destination |

While Table 4 exemplifies some of the metric definitions that were established, we note that these are only a subset of all the metrics formulated in total. In a similar fashion, we constructed metrics for every project listed in Tables 1 to 3, noting that those projects in bold were the focus of our investigation following this initial phase. As mentioned earlier, we then restricted our attention to those projects that were proposed within three cities: Los Angeles, Portland, and San Francisco. This allowed us to delve deeper into data specific to these three cities and ultimately create a comprehensive list of data sources that could support metric computation. We note here, however, that it is not always the case that there is sufficient data to produce a desired metric. But the process of establishing desired metrics is still useful because it helps to reveal data gaps that may be addressable through future research or improved data collection efforts. We explore these details in the context of specific metrics and supporting data sources in the following chapter.

## 4. Identified Data Sources and Gaps

In this section, we present the results of a broad search to identify existing data sources that could help to evaluate the desired metrics. Procedurally, this often took the form of searching open data websites for the three cities in our assessment. While this yielded useful information for certain metrics and projects, some of the required data were not publicly accessible. Additionally, several of the key data for certain metrics were considered to be project- or pilot-generated, meaning that the data are derived by the project itself. In these cases, there are no pre-existing datasets to support metric calculation by construction. In response to these limitations, we made assumptions about possible data structures and the discrepancies between what data might be available and what would be ideal for metric computation.

We also note that this list of data sources is not absolute or exhaustive and represents only sources that could be reasonably identified or assumed to exist. It might not include all possible data sources relevant to the metrics identified. We recognize that data are ever-changing — what was available at the time of this report will very likely change in the future, as new data types and sources are constantly being generated.

In the remainder of this section, we introduce specific metrics and supporting datasets within each data type category. We then provide a brief overview of how the data could be used to evaluate the metrics and describe any existing or potential limitations. The final part of this section is dedicated to identifying the common limitations and constructing a generalization of data gaps.

### 4.1 Crime Data

One measure of public safety is crime, generally measured as the number of instances or rate of occurrence. Crime data can be used to track criminal incidents that occur in regions served by a project. For example, cities and researchers are often interested in the overall number of criminal incidents that occur as well as the resulting number of injuries and fatalities. Some examples of possible crime-related metrics include:

1. Criminal incidents in regions served,
2. Injuries resulting from criminal incidents, and
3. Fatalities resulting from criminal incidents.

An evaluation seeking to understand a project's impact on crime may seek to identify any changes in these numbers from before and after the project implementation. Crime data are already tracked by police departments (for reported crime) throughout the country. For example, crime data are published on Los Angeles's open-data website and are available to the public without any restrictions. One limitation, however, is that there currently is no mention of injuries or fatalities within this public facing dataset. Moreover, crime data are often published by cities with open-data websites, but for the evaluation of broader regions, these data would need to be combined across all relevant cities and their varying structures might pose an additional obstacle.

Overall, crime data are often available to the public via open data websites. These data might not contain all necessary information to evaluate the metrics identified in this work. But for most applications, in which the count of crime instances is the primary metric of interest, existing datasets serve the core need of tracking events over time.

### 4.2 Crash Records

There are two main types of crash records relevant to the metrics identified in this white paper. The first consists of regional crashes that comprise all reported collisions that occur within an area of interest. The second consists of crashes that may occur within pilot studies of specialized vehicles. In both cases, cities and researchers are interested in the total number of vehicle involved in collisions, as well as the resulting number of injuries and fatalities. This information can be used to compare vehicle-involved collision injury and fatality rates within the project to measure performance over time or to generate comparisons of rates with similar safety measures for the population.

Regional crash records are tracked by transportation agencies throughout the country. For example, the Oregon Department of Transportation has a crash-data system, which contains a rich dataset with the necessary information to construct a variety of metrics. In addition, the California Highway Patrol (CHP) produces a comprehensive statewide dataset called the Statewide Integrated Traffic Records System (SWITRS). They have an open data policy but require data requests be sent after a formal request. Overall, regional crash records exist, but the availability of such records vary from state to state.

Pilot-generated crash records do not currently exist, except in those situations where pilots are currently underway. Even in these cases, the data structure is not defined. Pilot studies may or may not capture collision events, if they are not reported to the police. Thus, for pilot studies, one challenge can be collecting the attributes of collision data that would match those of public records. Such a challenge, however, is likely to be a concern in only a limited number of cases. This is in part because for all modes, millions of miles are usually traveled before there is a collision. Because of their infrequency, collisions with pilot studies will likely get considerable attention, and if reported to the police, would become part of the public records dataset. However, those datasets may not presently distinguish between the types of vehicles involved, such as human-operated vs. automated vehicles. That is, modifications may be required in certain jurisdictions to distinguish collisions with driverless technology.

### 4.3 Vehicle Activity Data

Vehicle activity data can be used to track the movement of vehicles within and outside of pilot projects. This type of information — consisting of origins and destinations, trip times and distances, and other fields — is essential for calculating metrics across a variety of impact categories. For example, consider the transportation metric defined in Table 4 as “passenger miles traveled (PMT) with SECA vehicles.” Vehicle activity data, which could track the total mileage associated with each trip, can be aggregated to give a moving sum of vehicle miles traveled (VMT) over the course of the pilot. If these data are occupancy-weighted by trip, then PMT can be derived. With vehicle activity data, cities and researchers can begin to understand how access to public transit and overall mobility has changed or improved, how the environment has been affected through an analysis of trip emissions and energy consumption, and whether any change in user behavior has helped to mitigate congestion.

Vehicle activity data are generated by pilot operators, so limitations related to using these data to evaluate the specified metrics ultimately depend on operators. In some cases, the operators may include public agencies, but more often they are private-sector companies that offer ridesourcing/TNC (e.g., Uber, Lyft) or carsharing (e.g., ZipCar, car2go, etc.) services. One limitation is that these operators can be uncomfortable or unwilling to share certain types of activity data, as it can sometimes reveal financial information or market performance to competitors.

Another potential limitation is the structure of activity data, as it varies across different operators. This can pose a challenge when considering that many of the same metrics are evaluated across a range of operators and projects. Some vehicle activity may be continuously recorded, while at other times it is only tracked at periodic intervals. Overall, the quality of activity data will range from operator to operator and project to project. Projects also need to address concerns of operators with respect to data security and disclosure of results. While evaluations may seek to generate the best possible insights from rich vehicle activity data, they must also ensure that they do not compromise the competitive positions of participating operators.

Private operators agreeing to data agreements with the public sector will likely be more receptive when cities provide a more detailed explanation of what data could be useful and why, allowing operators to provide aggregated data that is useful to cities without revealing sensitive information. Of course, this could pose limitations to other metrics of interest that require disaggregated data. Ultimately, compromises often need to be made between the public and private sectors.

## 4.4 Public Transit Ridership Data

Ridership data can be used to determine how a project has impacted access to public transit. This is particularly relevant for those projects that directly affect transit stations, such as the Integrated Carpooling to Public Transit MOD project (San Francisco Bay Area). Cities and researchers can compare ridership at relevant public transit stations before and after the project implementation. Specifically, it is useful to track counts of unlinked trips, defined as the number of passengers boarding transportation vehicles where passengers are counted each time they board a vehicle regardless of whether it was part of the same journey from origin to destination. This information can support determining whether a project improved access to public transit through an increase in the number of trips and travelers using relevant transit stations.

Ridership data are already tracked by transportation agencies throughout the country. For many agencies, disaggregated ridership data are held internally. However, aggregate ridership data are reported annually to the National Transit Database (NTD), as part of federal reporting requirements. Most agencies can provide more disaggregated ridership data, if necessary. In its simplest form, a daily count of unlinked trips by station is a sufficient input for the analysis of public transit ridership impacts. However, more precise data — such as the separation of access and egress or entrance and exit counts, as well as transfer counts over time — would be preferred as it would allow for a more comprehensive analysis of travel pattern impacts. Overall, ridership data exist and — if not already available — can sometimes be obtained through a request. Even if the data are not in the most preferable form, basic ridership data are essential for supporting the evaluation of many projects' impacts on public transit systems, which can have rippling effects on the environment, energy, and congestion.

### 4.5 Parking Data

Parking data for lots belonging to relevant public transit stations or parking spaces throughout city regions of interest can also provide much needed insight. Cities and researchers are specifically interested in the average usage rate of these parking spaces and, where applicable, the use of parking spaces by certain vehicle types. For example, in the Integrated Carpool to Public Transit MOD project (San Francisco Bay Area), it is of interest to track how many parking spots are used by carpooling vehicles versus personal vehicles. This will lead to an indirect assessment of how the project affects public transit use and the modes by which people travel.

Parking activity is often a more challenging data type to obtain within many urban environments. The tracking of parking activity requires sensing, which is deployed only in limited environments. Certain areas of San Francisco have smart parking capabilities, which include sensing to detect and report parking space occupancy. This was done through SFpark's pilot program, although the sensors were eventually turned off. At present, payment information is perhaps the most abundant information that can provide insights into parking activity. It is naturally only available in parking areas that require payment and where parking enforcement is sufficiently rigorous. Overall, the existence and availability of parking data are variable and depend on currently unknown circumstances. Thus, depending on the environment, it may be the case that some metrics can be evaluated while others are far more challenging. Since sensing for parking is presently very limited, parking activity are often only tracked in areas that require parking payment.

### 4.6 Survey Data

Survey data are critical for understanding the human response to transportation-related city projects. Surveys collect basic information about travel behavior that is not well measured through any other means with available data. For example, driving, bicycling, walking, and public transit use as associated with the individual is only captured through survey data, at present. Furthermore, changes in these activities due to the presence of a project intervention will, in all practicality, require the continued use of surveys now and into the future. Surveys can be deployed retrospectively, which ask people to recall how their behavior has changed over the course of a pilot project. Questionnaires can also follow a before-and-after design. This has the advantage of avoiding the recall of the respondent, but it is more complicated to implement and can encounter its own challenges with respondent attrition. Two key areas addressed by surveys in travel evaluations are: 1) user demographics and 2) travel behavior.

The collection of respondent demographics is necessary to understand the makeup of users participating in pilots, and it is often an essential component of assessing project equity implications. Surveys can also provide insight into participant user demographics in the pilot relative to the broader city or regional demographics. This comparison requires a pilot survey evaluation, since it is specific to the subset of users who participated in the pilot. Regional demographics, which characterize the population local to the pilot, can be obtained through the United States Census American Community Survey. This survey is updated annually for a wide array of demographic attributes. Depending on the scale, data may be available at 1-year, 3-year, and 5-year averages. At smaller scales (such as Census blocks), the Census aggregates respondents over time, since samples may not be large enough in small areas during a given year to estimate demographic distributions reliably.

While demographics are a staple of most surveys, travel behavior responses are also fundamental in that they provide a sense of how users have changed — or not changed — their travel patterns as a result of a project. Survey responses can be taken as before-pilot data, which are then compared to after-pilot data. This information allows us to estimate the change or impact on areas of interest like the environment and congestion. Overall, surveys are a critical part of any evaluation. They are required for the generation of metrics related to human behavioral change.

### 4.7 Trip Data

Trip data are analogous to vehicle activity data, but instead of being generated by the movement of vehicles, they are generated by the app or software used to book a trip. This is relevant to those projects that use trip planning apps, such as the proposed Multimodal Application and Data Marketplace Smart City project (Portland, Oregon). Depending on the resolution of information, trip data could contain much of the same information as in vehicle activity data — origins and destinations, trip times, modes of travel, distances, costs, and other attributes — as it is used to calculate metrics similar to VMT but for PMT.

One of the main differences between trip and vehicle activity data is that we cannot assume trip data will contain continuous location information as we might see in vehicle activity data. Whether this capability exists or not depends on the specifics of how the app records information and whether there is a shared database of information. For example, the trip data might only consist of one row per trip (e.g., trip ID, start and end time, start and end location, total cost, etc.). On the other hand, it could instead consist of multiple rows per trip, where rows are added from a variety of sources as the user completes different trip legs. The latter is ideal in that it is most similar to vehicle activity data, and it will be more conducive to evaluating metrics that require more comprehensive data.

Depending on the structure of trip data, cities and researchers could have difficulties deriving a small subset of the metrics, such as passenger travel time or speed. Overall, the quality of trip data will range from app to app and project to project. As with vehicle activity data from system operators, data from apps can be sensitive. Evaluation teams need to be cognizant of concerns raised regarding data security and competitiveness. With the right measures and protections, these concerns can usually be addressed effectively.

### 4.8 United States Environmental Protection Agency Data

Data assembled by the United States Environmental Protection Agency (US EPA) can be used to supply factors for environmental analysis. Broadly, EPA data can be used to determine the environmental impacts of a project through an analysis of trip emissions and energy consumption. While they need to be matched with other data sources — like activity or trip data that gives distance traveled, occupancy, and vehicle year, make, and model — EPA data are an essential component to understanding how the use (or avoided use) of specific vehicles has affected the environment throughout the course of a project.

The EPA fuel economy website is the most comprehensive public resource on vehicle efficiency. It contains the fuel efficiency factors for all vehicles sold in the United States. One limitation to this data source is that not all vehicles are contained within the searchable database. The most common case of this is when the vehicle was not released in the United States — usually because it was a slightly different version that was released in another country or sometimes because it is an entirely different vehicle. At present, it does not contain efficiency data for motorcycles or scooters. In these instances, it might be possible to find the vehicle specifications from other references on the Internet. For most studies focused on the United States or Canada, the EPA fuel economy database will cover the vast majority of the personal vehicle fleet.

### 4.9 Estimates of Vehicle Miles Traveled

Many projects require vehicle miles traveled (VMT) estimates to understand impacts on travel behavior, energy use, emissions, and congestion. While pilot vehicles with adequate vehicle activity data can account for VMT for within-pilot calculations, cities and researchers sometimes need a comparative estimate for VMT that accounts for non-pilot vehicles within the broader city or region. These VMT estimates can shed light on very localized impacts, such as within demonstration corridors where connected and automated vehicle technologies are deployed, such as in the proposed Connected Vehicles Smart City project (Portland, Oregon). Other times, the VMT estimate can be at a regional scale over time, such as in the proposed Fair Value Commuting MOD project (San Francisco Bay Area). These estimates, for example, allow for metric computation of the injury and fatality rates (number of incidents per mile) of regular vehicles (non-connected and non-automated). Comparing these rates to those generated by pilot vehicle activity data can illuminate whether the technology has positive impacts on safety in an urban environment. VMT is also an important measure itself as it quantifies vehicle travel and its effect on congestion and the environment.

While VMT is a critical component to the study of travel, it is surprisingly difficult to measure. There is a national estimate of VMT, which is a composition of measurements submitted by states, as well as sensors that all are part of the Highway Performance Measurement System (HPMS). Each state annually submits an annual average daily traffic count (AADT) for all of its road segments to the Federal Highway Administration (FHWA). These AADT counts are rolled up to produce a national annual VMT measurement. There are also about 4,000 automatic traffic recorders (ATR) that send data to the FHWA every month. These data are processed by the FHWA and inform monthly fluctuations from the annual

VMT measurement through an analysis of change rates reported by these sensors. This information produces the monthly estimates of total VMT published by FHWA's Traffic Volume Trends report. This monthly estimate is a "rolling sum" of the previous 12 months. Our experience has been that observations about one to two years old will undergo continuous revision as new information becomes available to the FHWA. After that time, measurements are rarely, if ever, revised. The USDOT has tracked VMT at the national scale for a very long time, given the scale of the task. While it is nowhere near a "precise" measure of all VMT, it is relatively reliable, and it can provide some context as to whether national VMT is rising or falling over time based on a relatively consistent approach. Localized measures of VMT, such as at the city or metropolitan area level, are very difficult to find and are usually infrequently made. This provides a considerable limitation to evaluating VMT at these localized scales over time. Technology may chip away at this problem. Nevertheless, despite its importance to policy and planning, the VMT of an area is still a very challenging metric to measure. While we expect emerging vehicle technologies, such as automation, to inherently track VMT, there is currently no adequate solution to estimating VMT for legacy vehicles. Cities and researchers can potentially rely on pilot-vehicle activity data or trip data to cover within-pilot calculations, but they lack the means to provide the same insight for non-pilot vehicles within the broader city or region.

## 4.10 Traffic Sensor Data

Traffic sensor data are generated by traffic counters placed on highways and throughout cities. Cities and researchers can use sensor data to infer general vehicle activity as well as their associated speeds within a specific area or corridor. Broken down by hour, this can be a useful measure for congestion. There are a number of issues that arise in using these data to evaluate the metrics identified in this study. Cities may have an uneven distribution of sensors with different capabilities. For example, traffic counters in Portland, Oregon, which are operated by the Portland Bureau of Transportation, have varying functions including: 1) volume (counts of vehicles), 2) velocity (speeds of vehicles), 3) classification (types of vehicles), and 4) bicycle counts. An additional requirement is that the location of traffic counters must align with pilot demonstration corridors or cover the areas that are serviced by a project, such as in the Connected Vehicles Smart City project that was proposed by Portland in their Smart City finalist application. Overall, sensor data exists but the locations and capabilities of the traffic counters that generate these data vary across jurisdictions. The usefulness of these data is thus project and city specific.

## 4.11 Usage Data

Usage data in this context refers to data collected from event tracking within multimodal mobile apps, WiFi kiosks, and other types of trip planning software. It is standard practice to implement event tracking when building software that interfaces with users. This built-in tracking is a mechanism that sends information to a database whenever a user accomplishes a certain task, dubbed an "event." Typical events that ping the database include when users download the software or open it on their device. For the purposes of many evaluations, the primary interest is in recording these general usage events, as well as more specific events that relate to the purpose of the software, such as when users route, book, or pay for trips.

Aggregating this information provides insight into software usage over time and could be particularly helpful in projects that are building on existing software and releasing updated versions. For example, it would be pertinent to compare the number of daily active users before and after an updated release. Software that has truly improved functional performance would likely yield an increased number of daily active users over time. We note that it is common to implement event tracking and that the specified metrics are standard key performance indicators (KPIs) for trip planning software, but these capabilities are ultimately dependent on the software engineering. Usage data, if it exists, can provide insight into how people use the technology and whether that use is consistent or changes over time. This is key to understanding the success of new software, whether it be within a smartphone app or fixed infrastructure, such as Wifi kiosks located throughout a city. Additionally, we note that one benefit specific to usage data generated by kiosks is that an analysis could identify which kiosks are used most frequently. This could help inform questions such as where additional kiosks (or other user interface infrastructure) are built in the future.

### 4.12 Generalized Data Gaps

In an attempt to summarize the information presented in our data source descriptions, we have identified different kinds of data gaps and categorized them into four distinct types. These are outlined as follows:

1. Measurement Gap
2. Spatial Gap
3. Temporal Gap
4. Disaggregation Gap.

It is first important to establish that "data gaps" are very context specific to analyses. A data gap for one analysis may be unimportant for another. Take for example, the measurement of VMT. For analysis of the economic determinants of movements of the national VMT estimate, there is not much of a data gap on the determinant variable. While we can debate the precision of this national VMT measurement, it does exist for a very long time series. But for VMT measurements at a local level, the VMT measurement gap is significant, since there is often no direct measurement of VMT presently available at this scale. Measurement gaps therefore arise when there is missing information that is required for metric computation. This can occur under a variety of different circumstances such as when there are: 1) few to no identified data sources for measurement, 2) identified data sources but with varying or unknown data structures (either because the data are pilot-generated and not yet in existence or because the data are not publicly accessible), or 3) identified data sources with an identified data structure but there are missing components in that structure that are necessary for metric computation. For some applications, all data sources have measurement gaps. We distinguish between measurement gaps that arise for these different reasons, respectively denoted by "existence," "uncertainty," and "structural" as listed in Table 5 below. There can also be overall gaps with respect to measurement precision and accuracy. Arguably, almost every data source has this gap for certain questions, and the level of precision required is a context specific need that is defined by those conducting the evaluation. For example, the EPA fuel economy database is very comprehensive across vehicle types, and it is good enough for most analyses evaluating emission changes resulting from variations in fuel consumption. Nevertheless, this too is an approximation, as the fuel economy of vehicles is subject to unique driving styles, traffic conditions, and vehicle maintenance. The combined fuel economy factors that we use are approximations that provide good enough answers for analyses focusing on the impacts of modal shift and changes in vehicle ownership. However, to evaluate an ITS project that smooths corridor traffic flow by reducing stop-and-go behavior, a more precise measurement of fuel economy and energy consumption is required, and the EPA fuel economy database by itself is insufficient to answer such questions.

Spatial gaps arise when the spatial scope of the data is not sufficient for metric computation. This occurs when the identified data source does not completely cover the geographic region(s) relevant to metric computation. For example, sensor data are generated by traffic counters placed in certain locations throughout a city. However, in order to be useful for our purposes, we would require that these traffic counters be placed in the exact demonstration corridors in which pilot vehicles operate. Spatial gaps can arise when the right data are collected by existing processes, but they are not in all the locations in which they are needed.

As with the spatial gap, temporal gaps naturally arise when the temporal scope of the data is not sufficient for metric computation. For example, crash records are often updated yearly in an online database, so the most recent crash records might be unavailable. In these cases, we lack access to data that covers the desired timeframe.

Disaggregation gaps arise when the data are not disaggregated to an extent that is sufficient for metric computation. This occurs when the data does not provide adequate detail — that is, each data point represents the aggregation of more specific data, and there is no way to revert back to its original form. This is best explained through our example of VMT estimates as described in Section 4.9. Even though there is a national estimate of VMT based on estimates at the state level, we lack the ability to further disaggregate the data to a city or intra-city level. This lack of detail, or inability to disaggregate the available data, illustrates the concept of a disaggregation gap.

In Table 5 below, we indicate instances of spatial, temporal, and disaggregation gaps with checkmarks. We also present characterizations of the measurement gaps. For context, these were identified for the data sources that would be needed for the specific projects explored in this analysis, and by no means characterize data gaps as generalized for all types of analysis.

**Table 5 Data Gaps for Each Data Source Type**

| Data Type | Measurement Gap (None/Structural/Existence/Uncertainty) | Spatial Gap | Temporal Gap | Disaggregation Gap |
|---|---|---|---|---|
| Crime data | Structural | | | |
| Crash records | Uncertainty | | | |
| Pilot vehicle activity data | Uncertainty | | | ✓ |
| Public transit ridership data | Uncertainty | | | |
| Parking activity data | Uncertainty | ✓ | ✓ | |
| Survey data | Uncertainty | | ✓ | |
| US Census data | None | | ✓ | |
| Trip data | Existence | | | ✓ |
| US EPA data | None | ✓ | | |
| Local population VMT | Existence | | | ✓ |
| Traffic sensor data | Structural | ✓ | | |
| Usage data | Uncertainty | | | |

While Table 5 provides a general understanding of the data gaps that exist for certain data sources, it also illustrates another important point. As we know, there are several different versions of each data source that correspond to the different projects, cities, and data-generating entities. For example, we may desire crash records for Los Angeles as well as for San Francisco to compute the very same safety metrics for comparative performance purposes. In theory, we could compare the same metrics for each of the key objectives across multiple cities. But the data sources are currently a barrier to such comparisons. The data sources must be specific to the region of interest (in this case, Los Angeles vs. San Francisco) and hence do not lend themselves to generalization. As shown in Table 5, every data type included in our assessment has one or more gaps. Many of the core transportation data in pilot projects are generated by public or private sector operators or smartphone applications. As shown in Table 5, these data types have "uncertainty" content gaps, meaning the data source has an unknown or undefined structure, either because the data are pilot generated and not yet in existence or because the data are not publicly accessible and are stored within some agency or company. As a result, comparative performance analyses are not currently possible.

This was a key issue that arose in our investigation. This issue presents itself whenever we attempt to generalize findings for specific data sources. For example, in Table 5 we see that a "structural" gap is indicated for crime data. While this is true specifically for Los Angeles's open-data website — which lacks information about injuries and fatalities within the crime data — this is not true for all crime data. Ultimately, this issue is unavoidable, and we note that Table 5 only provides a high-level understanding of potential data gaps.

Another issue that we came across is the notion of varying data structures. As mentioned previously, different versions of the same data source type do not necessarily contain the same information. We might have more information in one version, which allows for metric computation, while we have less information in another, which creates a data gap that prevents metric computation. These varying data structures are problematic in that they complicate metric computation and require a case-by-case assessment of what can be achieved.

One outcome of our investigation was the proposal of data structures that were ideal for metric computation in cases where the actual data structures were not accessible. Since this task was inherently metric focused, we do not necessarily expect the actual data structures to reflect these proposed structures. However, this exercise was useful because we were able to identify the exact elements of information necessary to calculate the desired metrics. These proposed data structures can provide guidelines for advancing better data quality for project evaluation.

A final issue that we consistently encountered was limited data accessibility. While there are a number of data source types that are commonly published on open-data websites (crime data, crash records, etc.), there are many more that are not. As there is a shift toward more open and shared data across sectors, it is possible that the number of publicly available data sources may increase. At the same time, the advance of public-private partnerships within the transportation sector may enable the establishment of common ground on data agreement. While most private entities encourage evaluation of their impacts, they also encounter threats and challenges that can impact revenue if the wrong information is compromised (e.g., personally identifiable information or proprietary data). This issue, if not properly worked out, could limit the ability of cities to evaluate and understand the systems that they are piloting in the coming decades.

## 5. Conclusions and Recommendations

Data are essential to provide an evidence-based approach for cities to measure the impacts of transportation projects and pilots as they relate to civic priorities. This white paper assesses a series of projects and applications that comprise near-term smart city concepts or pilot projects underway. Many of these pilots directly address the climate and social impacts of transportation, and they are expected to be a first step toward generating the data needed to inform smart policy. We provide an evaluation framework that can be used for assessing project impacts within the context of the Smart City and MOD Sandbox projects, as well as other transportation-related city projects. The evaluation framework presented here is a major step toward facilitating the establishment of rigorous and thoughtful data collection practices, enabling future city planners, policy makers, and practitioners to understand and collect the right data needed to evaluate and monitor the performance of emerging innovative transportation projects. Nevertheless, many of the smart city concepts and pilots are focused on one individual segment of the transportation sector, resulting in a broad range of disparate data metrics.

There is a clear need for cities and researchers to assemble the mosaic of data and make it useful for data sharing, analytics, and visualization for residents, governments, researchers, and industry. As evaluations rely so heavily on data, limitations will inherently arise depending on data availability and data quality. There are select instances of metrics that are difficult to calculate within certain contexts.

However, as we move toward a more data driven future, we expect that these instances will become sparser and the data will become richer.

Our analysis revealed that many of the core data in pilot-projects are generated by public or private sector operators or smartphone applications. We identified that these data often have measurement gaps, meaning there is missing information that is required to compute the core metrics. Due to the groundbreaking nature of these emerging projects, gaps in data measurement typically arise because the data are pilot-generated, not yet in existence, or because the data are not publicly accessible and reside within an agency or company. This creates significant challenges to conduct cross-city comparative analyses.

Applying this or similar evaluation frameworks to smart city pilots and projects can lead to more robust analysis and understanding of the environmental and social impacts of emerging innovative mobility. To the extent that these analyses are public-facing, the process will permit a broader community of cities to learn, accelerating the national scale-up of innovative mobility solutions and maximizing environmental and social benefits.

Policy and smart government actions can help overcome some of the key challenges and limitations identified in this white paper. One common challenge across all pilots is collecting the attributes of various data in a way that matches public records. Careful planning, communication, and collaboration across project managers, chief data officers, and relevant agency stakeholders are needed for scaling up pilots and integrating them into the broader data and transportation system. Another challenge is the existence of multiple data structures for the same data type. As such, we propose data structures that are ideal for metric computation, ultimately hoping that these can help guide future policy and data engineering, as well as provide a basis for standardization.

There are a number of recommendations that stem from this analysis. One is that cities and researchers should explore existing data gaps even before there is a project to evaluate. Cities do not have to wait for a project to be proposed, funded, and implemented to ask core questions about what data are available to measure common metrics, which are almost always part of an evaluation. For example, cities can seek to establish ways to generate localized measurements of VMT, PMT, and other travel behavior metrics, which can establish benchmarks for any subsequent project impacting transportation. The continuous measurement of key benchmarks will better enable evaluations that draw from a deep resource of before data. Cities and researchers should also consider the types of data structures that they might need to efficiently address questions. Some data structures need only be established in the form of distributions, while others may require the presence of more detailed and anonymized activity data. Finally, cities and researchers can do their best to generate key questions of interest at the beginning of an evaluation, which play a major role in guiding decisions about needed supporting data. The sooner these questions are raised (even if they are general), the sooner data needs and structures can be established. Smart cities will perform better if they can appropriately define data needs as early as possible and pursue efforts to collect, improve, and evaluate them over time.

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