WORKING PAPER

Citywide Transportation Greenhouse Gas Emissions Inventories: A Review of Selected Methodologies

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INTRODUCTION

The transportation sector accounted for 14.3% of world greenhouse gas (GHG) emissions in 2005, behind electricity and heat (24.9%) and industry (14.7%), but ahead of agriculture, land use change, and waste.[1] As one of the three highest emitting activity sectors, transportation is an important field to target for emissions reductions strategies. It is even more crucial in the United States, where its share of emissions is considerably higher than in the rest of the world. The US transportation sector accounted for over 33% of total nationwide CO_2 emissions in 2008.[2] Urban passenger transport in the US represents almost half of total transportation emissions, and around 15% of total CO_2 emissions, according to the Environmental Protection Agency (EPA).[3,4]

The ability to perform accurate transportation emissions inventories at multiple geographic levels and update them regularly is critical for identifying opportunities for emissions mitigations activities, as well as for measuring their progress over time. EMBARQ – The World Resources Institute Center for Sustainable Transport is engaged in this area in order to assist local and national governments around the world to reduce GHG emissions. Reductions in GHG emissions represent one of the key performance indicators across all EMBARQ projects, from the low emissions zone in Istanbul's historic peninsula to Bus Rapid Transit (BRT) corridors across Latin America and Asia.

A citywide transportation emissions inventory is critical in order for local actors to understand the magnitude of transportation emissions and evaluate the relative contribution of different factors to overall emissions. Furthermore, an accurate inventory is an essential step in developing a comprehensive climate action plan, an effort that many cities, regions, and states are undertaking.

Developing an inventory involves making important decisions about which emissions from what trips to include, what the boundary should be, and what data collection method should be used. Depending on how it addresses these different issues, an inventory for the same city or metropolitan area can report significantly different results. In this paper, we analyze the main methodological issues involved in making an inventory and explore how they can influence the inventory's results. There is no single way to address all these challenges successfully, and each city's decision on how to develop a methodology for creating an inventory will depend on the local political and geographical context, as well as data availability.

In the second part of the paper, we review several methodologies currently used around the world to develop citywide transportation emissions inventories, including international methodologies such as the World Bank Citywide Methodology, the European Commission's COPERT model, as well as inventories developed by local planning agencies in San Francisco and Lisbon. These inventory methodologies vary significantly in terms of scope, data requirements, and data collection methodology. They also illustrate the diversity of approaches currently used around the world to track urban transportation emissions.

Finally, we discuss how transportation GHG emissions inventories could be integrated with climate policies in the US and internationally, noting that inventories would be particularly useful in implementing performance-based transportation funding, where federal funding would prioritize funding for projects that reduce GHG emissions. In the developing world, inventories provide the information that can inform emissions-reduction strategies and, when repeated over time, can help monitor the effect of projects and policies aimed at reducing emissions. This can help cities plan for GHG emissions reductions and apply for transportation-related Nationally Appropriate Mitigation Action (NAMA) financing.

CREATING AN INVENTORY: METHODOLOGICAL ISSUES

Creating a transportation GHG emissions inventory involves making a series of decisions on the following issues:

- The scale at which the emissions will be measured (neighborhood, city, or region[5]);
- The method for measuring emissions (top-down, e.g., based on regional fuel sales volumes, or bottom-up, e.g., estimating total vehicle kilometers traveled [VKT] in a city or region based on surveys or traffic counts);
- The data collection method (using existing data, travel surveys, odometers, etc.); and
- The timeframe for monitoring emissions (how often to repeat the inventory to track changes).

Depending on the method chosen for creating the inventory, the results can be significantly different. Christopher Ganson illustrates this by comparing the results of four different emissions inventories for the city of Berkeley, CA.[6] When using an inventory that considers only those trips that occur entirely within the city limits, annual citywide transportation GHG emissions total 292,707 tons for 2005. If, however, the inventory is expanded to also include trips to and from nearby cities, allocating half of the emissions from each of those trips to Berkeley, total annual emissions increase significantly to 434,705 tons.[7] The major difference between the two results can be explained by the fact that Berkeley is an employment center and a major regional destination in the San Francisco Bay Area, attracting trips from other cities in the region, such as Oakland, Richmond, or Fremont.[8]

Since different methodologies can produce significantly different inventories, the chosen methodology can have a large impact on the set of strategies chosen by a city or a region in developing a comprehensive climate action plan or undertaking stand-alone transportation GHG emissions mitigation actions.

What is the appropriate boundary and how should trips that cross it be addressed?

Creating a transportation GHG emissions inventory involves making important decisions on where to draw the boundary between emissions that are associated with the transportation sector in a given city and those that are not. The most important boundary is the geographical – how to count trips that do not occur wholly within the city in question. This includes commuting or shopping trips from other parts of the region, but also trips to and from major airports, which are usually located outside the administrative limits of the cities they serve.

There are two important issues to be considered here. The first issue is how to correctly allocate emissions from a trip that crosses multiple cities to each of those cities. The second issue is making sure that the attribution method agreed upon does not result in double-counting emissions when they are aggregated back to the regional level.

Researchers have proposed a variety of ways to address these two issues (Salon et al. 2008, Ganson 2008, Millard-Ball 2007) both in terms of how to collect information on emissions and also how to allocate it to individual cities. When considering how to allocate emissions from a multi-city trip, an important issue to be addressed is which cities have the power to influence those emissions. Clearly, the origin and destination cities have the most leverage, as they can enact transportation and land use policies to encourage alternate modes. The cities crossed by the trip have less influence on the trip itself. They could, for example, impose pricing on the transportation corridors that cross them, but the trips may simply be diverted to other routes. For this reason, the examples cited below generally recommend attribution methods that divide emissions only between the origin and destination cities.

Deborah Salon et al. present an overview of the different ways to allocate emissions from multi-city trips and the emissions measurement or estimation methods associated with them.[9] The options presented are analyzed according to three criteria: the degrees to which they enable accurate local VKT measurements, maximize the options for local governments to reduce VKT, and avoid local policies that might increase emissions at the regional level.

The first allocation method presented is the most direct one – allocating emissions from a trip to all cities crossed, directly proportional to the length of the trip segments in each city. Emissions would be estimated based on measurements for vehicle type and local VKT,[10] which could be estimated via loop detectors[11] in conjunction with travel demand models. The weakness of this method is that VKT would be allocated to traversed cities that are neither origins nor ends for those trips, and as a result have fewer options for affecting the emissions from those trips.

The second method assigns VKT according to where vehicles are fueled. This approach would represent a gain in precision compared to the previous method, as fuel sales can be measured accurately, but it would pose the same problem related to through traffic as the previous option.

The third option uses odometer readings to assign VKT and emissions to the locality where vehicles are garaged. The authors argue that this method would provide incentives for land use changes and alternative transportation near home locations, but it would not provide the same incentives near work or shopping locations.[12] Salon et al. propose an assignment method based on odometer readings allocated by vehicle home locality, with an adjustment for new non-residential development within that locality. The authors argue that this would add incentives for mixed-use development near home locations.[13]

A different accounting method has been proposed by Ganson[14] and Millard-Ball.[15] It allocates half of VKT and emissions to the locality where the trip originated and half to that where it ended. Known as the trip-end attribution method, this approach would allocate emissions to those cities that have the most influence over them. It also has the advantage of attributing all the emissions from an intra-city trip to that same city, without double counting. While previous allocation methods involved odometer readings and loop detector data, the VKT estimates for this case would rely exclusively on regional travel demand models and might therefore provide inaccurate information at smaller scales.[16]

The trip-end attribution method would not allocate emissions to those localities that are only traversed by trips and that do not constitute origins or destinations, as it assumes localities have little influence over these emissions. While this applies to car trips, it may not be true for transit trips. If a city is traversed by a transit line, even if it does not contribute to the ridership of the transit system, the city has an opportunity to promote transit-oriented development along that transit line and potentially reduce transportation GHG emissions on a per capita basis. To ignore this trip segment in allocating VKT and emissions is to overlook an important opportunity to increase transit ridership. This would only make sense in the unlikely event that it would not be feasible for the transit system to place stops in that specific locality. An alternative method would be to allocate emissions to all localities traversed by a transit line on a per-kilometer basis. For example, if 60% of the length of a bus line is in city A and 40% is in city B, then 60% of the emissions from that bus line would be allocated to city A and 40% to city B. This would more closely reflect the opportunities afforded by the presence of an existing transit network.

Which transportation sub-sectors and trip types should be included in the inventory?

After determining the geographical boundary of the inventory area, and deciding how to account for trips that cross the boundary, the next important issue to address is whether the inventory should be limited to urban passenger transport, or whether it should be broadened to include all passenger and freight transport to and from the city.

For example, should an inventory for New York City consider the emissions from flights originating or ending in its three major airports? Moreover, should the ground transportation and freight handling facilities at a major airport be considered part of a city's transportation system or part of the airport complex? These are emissions directly associated with the movement of passengers and goods in and out of the city, but the city may not be able to enact policies influencing those emissions, whereas the agency overseeing the airport could. A comprehensive global inventory of transportation emissions would have to include inter-regional and international air, water, and rail transport. Including those in a citywide inventory, on the other hand, may not always be a useful tool for informing emissions reduction policies. While it would be fairly straightforward to determine how to attribute emissions from international trips to individual cities (by allocating, for example, half of emissions to the origin city and half to the destination) it is not clear that cities can always influence emissions from international air travel.

Including emissions from the transport of freight can pose a number of challenges. The main issue is how to allocate emissions from a good that was, for example, manufactured in China, transported by ship to the US, loaded on a truck, and then delivered to a retail facility within a city. The city,

Lifecycle Emissions

Many existing inventory methodologies account only for GHG emissions from 'active' vehicle operation, and some also include 'inactive' operations. For a holistic view of transportation emissions, it would be important to consider total lifecycle emissions. In a study on the environmental assessment of passenger transportation, researchers from UC Berkeley argued that a vehicle lifecycle analysis should include extraction of raw materials, construction, operation, maintenance, and end of life for vehicles as well all products and services required to operate them, such as infrastructure and fuel. The authors have found that when considering all these factors, active vehicle operation represents only 65-75% (for cars, trucks, and buses) and 24-39% (for rail) of total lifecycle emissions. (Chester, Mikhail, and Arpad Horvath. 2009. Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environmental Research Letters* 4:2) having control over land use, could implement smart growth policies, and the delivery vehicle could travel over a shorter distance within the city's boundary to reach its destination. But this would address only a small portion of the total emissions associated with transporting that good. The EPA proposes a method for estimating GHG emissions from the provision of goods and food for the US. The method stipulates that "emissions that occur in other countries to produce or transport goods and services that are consumed in the US are not captured in the US inventory."[17]

One way for a city to address these issues would be to enact local regulations promoting the use of local goods, produce, and materials. By providing enough incentives, the city could encourage residents to rely more on these local products. Globally, emissions would be reduced since freight would be transported within the region instead of around the world to reach that city. However, the citywide inventory might report an increase in emissions, since it would capture all the new local freight transport, and would not be able to detect reductions in long distance transport occurring outside its boundaries. A system of emissions credits could be useful in this case, applied to each local trip that is likely to offset a longer international trip. This way, even if the inventory would report an increase in emissions, the credit system would offer an estimate of the global benefits related to that local increase, recognizing the merits of the local use policy.

Waste transport is another topic of interest. According to the EPA, landfill capacity is very limited in some areas in the United States.[18] The *New York Times* reports that New York City sends over 10,000 tons of residential waste per day as far as Ohio and North Carolina.[19] In this case, there would be an opportunity for the city to reduce emissions by minimizing the need to transport waste to distant landfills. This could be achieved by reducing the volume of waste or investing in local waste-to-energy facilities. It should be noted here that implementing such a solution would require good integration between municipal agencies – not just the Department of Transportation.

There are other kinds of transportation emissions that should theoretically be part of a citywide emissions inventory, but that cannot be influenced through transportation policy. For example, the transit portion of the transportation GHG emissions inventory created by the Metropolitan Washington Council of Governments (MWCOG) Transportation Planning Board (TPB) estimates emissions from public transportation by counting only tailpipe emissions from buses.[20] The developers of the inventory have chosen not to include the emissions related to the electricity used to power the subway system and the different display boards for both buses and the subway. These emissions are directly dependent on the type of fuel used to generate electricity in the city and are not addressed in the same way as tailpipe emissions from buses. In this case, the goal of the inventory was to account for all GHG emissions that could be influenced by the TPB.

As in the case of defining the boundary, we suggest that the guiding influence on the choice of which sub-sectors to include should be which agency or government body is best suited to address each sector's emissions.

What is the appropriate scale for an inventory?

Assessing the appropriate scale for inventories can also provide an assessment for what level of government is well positioned to conduct (and receive funding for) transportation emissions mitigation projects. The issue of scale is particularly important in urbanized regions containing multiple cities, where multiple levels of local and regional government can implement emission mitigation strategies. In the US, cities have control over land use and local transportation projects, while Metropolitan Planning Organizations (MPOs) can influence major transportation investments and the state governments control many roads. Cities, MPOs, and states can enact policies that reduce emissions related to transportation, although they have different methods.

Within larger urbanized regions, it is possible for a city to implement a local policy that will reduce emissions locally, such as a congestion pricing scheme for a given area.

However, this policy could divert traffic to neighboring cities and potentially increase or redistribute emissions at the regional level. Thus, when creating inventories for a part of a larger urbanized region, researchers, consultants, and planners must analyze where to draw the geographical line when assessing a city's effect on, and responsibility for, transportation emissions.

There is a clear advantage in choosing to develop an inventory for a wider area: the area of the inventory would more closely approximate the regional travel shed.[21] Cross-boundary trips would become less important as they would represent a small fraction of total trips with the larger boundary. Issues such as how to allocate emissions from multi-city trips and how to correctly aggregate them back to the regional level would no longer be as important as in a citywide inventory. The main drawback is related to the political structure of the region: if the regional government has less decision-making authority than the individual cities, a regional inventory is not as useful as a citywide one for guiding transportation policy.

How often should an inventory be updated?

The San Francisco Department of the Environment is developing a transportation GHG emissions inventory for the city of San Francisco, which is expected to be updated every five years.[22] This timeframe might be suited for cities in the US, many of which are no longer experiencing significant growth and where car ownership rates are expected to remain steady in the near future. Applying the same method in the developing world, however, might lead to inaccurate results. Between 2000 and 2003, vehicle ownership in China increased at an average rate of 13,000 vehicles per day.[23] In major cities, such as Beijing, as many as 1,000 new vehicles are added to the city streets each day.[24] As a result of increased motorization, annual VKT is likely to change significantly over short periods of time. This would indicate the need to update an inventory frequently, possibly even every year. However, the time and cost of gathering vast amounts of data might make it impossible to update a comprehensive transportation emissions inventory annually.

One solution is to prepare a comprehensive update every five or ten years, based on citywide models or travel surveys, and a less sophisticated update every one or two years, based on a methodology that is less comprehensive, and also less time consuming. An important issue is how much less detailed an inventory can be while still providing useful information for implementing or assessing projects and programs.

The Clean Development Mechanism (CDM), a framework developed under the Kyoto Protocol to allow industrialized countries to invest in emissions reductions projects in developing countries, requires the use of baselines in order to measure emissions. Under the CDM methodology, the baselines are normally updated at the renewal of the credit period (every seven years), although some methodologies specifically require annual updates.[25] Transportation emissions inventories could be useful in getting transportation projects accepted under CDM, though the timeline and the frequency of updates will then have to meet CDM requirements. The integration of inventories with international climate policy is discussed in more detail later in this paper.

What is the best timeframe for assessing changes in emissions?

In their analysis of emissions from urban passenger transportation in Indian cities, researchers at the Center for Sustainable Transport (CST-India), a member of the World Resources Institute's EMBARQ network, developed emissions forecasts over 35 years, creating an inventory for 2005 and comparing it with predictions for 2020 and 2040. They estimate that per capita emissions from transportation in Mumbai will grow from 132 kg CO_2 per person per year in 2005 to 490 kg by 2020 and 1,011 kg by 2040, under one of the proposed scenarios.[26] The choice of such a long timeframe is justified by the significant increases in emissions that are expected during this time.

The choice of time period over which to monitor emissions can significantly influence results. For example, a freeway-widening project might reduce emissions in the short term by improving traffic flow and eliminating delays. Over the long term, however, the project might attract new development along that freeway, or attract traffic from other places in the region, and increase emissions. Therefore, only a long term monitoring effort would capture the actual effect of the freeway-widening project on GHG emissions.

How should an inventory update account for increasing urban population?

An update to an existing inventory may have to deal with changes to the population of the city. If the population grows, the total emissions from transportation are likely to rise. However, as Ganson notes, a city's choice to accommodate more residents does not generate additional population, but simply determines how the growing population is distributed.[27] If the new residents are moving from a suburban location to a compact city center, their travel behavior is likely to change and their per capita emissions could be lower than at their previous location.[28] In order to account for this, Ganson suggests a system of emission credits. By estimating citywide GHG emissions, he found that a person in Berkeley, CA emitted a total of 2.6 tons GHG per year, while a resident of Vallejo, CA emitted 7.1 tons GHG per year.[29] Therefore, if a resident of Vallejo moved to Berkeley, overall emissions in Berkeley would increase, but per capita transportation emissions, measured at the regional level, would be expected to decrease.[30] While overall emissions inventories are helpful for estimating reductions needed over time or benchmarking, per capita reporting is equally important, to show changes in per capita emissions.

What is the best way to report GHG emissions in an inventory?

There is no agreement in the literature on what is the best unit of measurement or indicator to evaluate transportation emissions. In a study of CO_2 emissions from urban transportation in Chinese cities, Darido et al. used a number of different indicators, from CO_2 per person trip to CO_2 per unit of metropolitan gross domestic product (GDP), and found that the different indicators often showed conflicting results. Using one method of measurement reported a decrease in emissions, while another method reported an increase.[31]

Most inventories report results as overall transportation GHG emissions by applying emission factors to VKT data obtained from counts or travel models. The results can be expressed as overall GHG emissions or GHG emissions per kilometer traveled. However, these results fail to provide information on the number of passengers that the transportation system carried. Therefore, if a city implemented a policy promoting transit use and transit ridership increased as a result, an inventory that reports overall transit emissions might not detect this change. That inventory may even report an increase in transit emissions, if the transit agency responds to increased ridership by adding more vehicles to the transit fleet, or increasing service frequency.

Chester and Horvath suggest measuring transportation emissions on a passenger kilometer basis. Using this system, they are able to show that, for example, an urban diesel bus during an off peak period, when it carries fewer passengers, emits 56% more GHG emissions per passenger kilometer than a conventional gasoline SUV. However, the same bus during the peak hour, when it has a higher occupancy, emits only 20% as much as an SUV, when emissions are divided by the number of passengers in each vehicle.[32]

We argue that every inventory should include a measurement of emissions per capita. This approach allows the developers of the inventory to control for changes in population, and also provides a simple way for comparing the magnitude of transportation emissions over time, against other sectors, or compared to other cities. This observation is especially useful for inventories that look not only at transportation, but also other sectors, since it eliminates difficulties in comparing sector-specific measures of energy and emissions, such as g CO_2/kilometer from transportation with kW/m^2 or g CO_2/m^2 from buildings.

DATA REQUIREMENTS

Schipper proposed a methodology for inventorying GHG emissions from transportation based on four factors, known as the "ASIF identity."[33] According to this method, total transportation emissions (G) can be calculated according to the following formula:

G = A x S x I x F where

- A = Total transport activity
- S = Vehicle kilometers and passenger kilometers by mode
- I = The energy intensity of each mode
- F = Emissions per unit of energy or volume or distance

A transportation GHG emissions inventory is based on the combination of these different measures of activity and vehicle characteristics. Another important factor that affects activity level and emissions rates is driving behavior, which also influences emission factors.

By combining data on volume of travel with emission factors, inventories can report overall transportation GHG emissions. In order to be able to report transportation GHG emissions on a per capita basis, it is equally important to include data on vehicle occupancy. Local data on travel speeds and congestion levels within the city can also increase the accuracy of the report.

An inventory methodology designed to be easily generalized using readily available data needs to be flexible in terms of its data requirements. Depending on whether it needs to be generalized for the US, Europe, or the entire world, the inventory will have to work with very different levels of data availability and accuracy. It is therefore important to consider the tradeoff between accuracy and ease of use when considering the possible application of this methodology to developing countries.

DATA COLLECTION METHODS

Local governments typically have little control over the environmental performance standards of private vehicles, although this could change with the implementation of plug-in electric vehicle incentives. Until robust implementation of vehicle incentives, which could be years away, the emissions parameter that can be most influenced through local transportation and land use policy is the volume of travel, or total transport activity. Cities can enact policies to reduce travel distances by promoting compact, mixed-use development, or increase average vehicle occupancy through policies favoring transit, carpooling, vanpooling, and road pricing. In order to inform such policies, a thorough inventory should provide detailed reports on travel patterns throughout the city.

Regional travel demand models are one possible source for obtaining vehicle travel data at the city level. However, these models estimate VKT at the regional level, aggregating data from traffic analysis zones (TAZs). The problem is that the boundaries of the TAZs do not always overlap with those of the cities in that region. Obtaining a VKT estimate for a city based on a regional model will therefore have a high degree of uncertainty. Moreover, regional models are usually insensitive to local features, such as mixed-use

Using Mode Split as a Proxy for GHG Emissions

In a study of opportunities for transportation GHG emissions reductions in Brazilian cities, Dario Hidalgo, Toni Lindau and Daniela Facchini developed a methodology for tracking changes in GHG emissions over time. For the base year, VKT and travel time are estimated using a travel demand model. After extensive data collection, the model is calibrated to reproduce observed travel patterns. The calibrated model is then used to estimate GHG emissions from transportation for the base year. Changes in emissions over time are estimated by using a simplified approach that involves monitoring certain key indicators, such as population, GDP, mode split, trips per person per day, average trip distance, etc. (Huizenga, Cornie, and Stefan Bakker. 2010. *Applicability of post 2012 climate instruments to the transport sector July 2010.* http://cleanairinitiative.org/portal/sites/default/files/slocat/CITS_Report_ADB_IDB_SLoCaT_July_2010.pdf) transit-oriented development (TOD) around transit stations, or changes in the pedestrian environment. These features can impact travel volumes and travel behavior at the neighborhood level, but regional models do not have the capacity to detect changes at such a small scale. It should be noted, however, that these models are constantly being updated and refined. Moreover, researchers have developed post-processing tools and alternative approaches to more accurately capture the transportation demand impacts of neighborhood-scale projects and interventions.[34]

Fuel sales are another source of information used in inventories, often used to validate data obtained from bottom-up approaches (such as estimations of VKT in a region). The problem with this method is that fuel sale data is not geographically precise. Knowing where a car was refueled does not offer information on where that car was driven, and therefore does little to inform local GHG emissions reduction policies. This method would be appropriate only if the inventory is developed at a very large regional scale, where it would be less risky to assume that cars were driven in the same region where they were refueled.

A number of other methods exist for measuring or estimating transportation GHG emissions, ranging from the sophisticated satellite image tracking combined with GPS-equipped cars used by Portuguese researchers to develop an inventory for Lisbon, to the simple household travel survey used by CST-India. Salon et al. provide a list of different methods available for obtaining data for inventory creation. This includes loop detector data, fuel sales, average fuel economy, odometer readings, travel surveys, and travel demand models.[35]

In the US or Europe, the choice of data collection method is closely associated with the VKT measurement method chosen. If a locality chooses to monitor VKT for all trips originating inside its boundary, it might opt for using odometer data. If, on the other hand, the goal is to estimate travel only within a geographical boundary, loop detector data might be the appropriate method. In the developing world, where data is not as readily available, inventories often rely on using whatever type of data is available. For the CST-India model, the researchers used travel surveys and data on vehicle occupancy, relying on assumptions about trip distance, mode split, etc.

The developers of the International Vehicle Emissions (IVE) model, an inventory methodology specifically designed for the developing world, note that one of the biggest challenges in adapting an existing model to a developing country is obtaining local data on the vehicle fleet and associated emission factors.[36] The researchers have therefore developed a data collection methodology using resources typically available to developing nations. This involves a six-day field study designed to collect as much initial data as possible. A sample of streets in each city is videotaped, providing information on mode split, composition of the vehicle fleet, traffic volumes, and average speeds. In addition, parking lot surveys are carried out in the area, with a mechanic inspecting each vehicle in order to record data on vehicle make, model, engine type and size, etc. Based on the information gathered from the field study, the IVE model can be used to provide an accurate estimate of emissions for the selected region.[37]

In order to understand driving behavior, IVE researchers used GPS technology while riding in or driving different vehicle types. In addition, Vehicle Operating Characteristics Enunciators (VOCE) were fitted to volunteers' vehicles, in order to record the engine stop/start patterns for the vehicle fleet.[38] The IVE method is therefore capable of acquiring large volumes of data, with a considerable level of detail related to driving behavior, vehicle stock, and vehicle operating parameters, using considerably less sophisticated technology than, for example, the Portuguese model. An interesting next step would involve applying the IVE and the Portuguese method to the same area, to compare the differences between the two different approaches.

PAST AND CURRENT INVENTORY EFFORTS

Citywide transportation GHG emissions inventories are an emerging field, with multiple inventories in development around the world. International organizations such as the World Bank and the Global Environment Facility (GEF) are developing methodologies for their institutional use. Cities such as San Francisco and Lisbon have also developed unique inventory methods, suited to their geographical context and policy objectives. The different local, national, and international agencies currently involved in developing inventories are not always aware of each other's efforts, and there is no internationally agreed-upon "road map" for creating such an inventory. For this reason, the existing inventories tend to be very different in methodology, data requirements, and scope, making comparison difficult. While some of them are specifically tailored to a single city, others are designed to be flexible tools adaptable to multiple countries. Some methodologies aim to make inventories from different cities comparable, while others are more focused on developing tools to track changes in emissions over time in one place. Some of them focus only on GHG emissions, while others include pollutants that are relevant for local air quality.

The eight inventories discussed in more detail in this section have been selected for their relevance to both the developed and the developing world, and for the interesting methodological insights they provide. The goal is to review a sample of inventory methodologies sufficiently diverse to illustrate the different challenges involved in developing an inventory, and different ways to address these challenges. This discussion does not constitute a comprehensive summary of all the inventories currently used around the world. Bader and Bleischwitz provide an evaluation of several other inventories, with a focus on Europe.[39]

ICLEI - Local Governments for Sustainability

Scale	City or county
Data requirements	VKT or fuel sales data
Data collection method	Not specified
Limitations	Ignores freeway traffic and trips that start or end in other jurisdictions

ICLEI has developed the Harmonized Emissions Analysis Tool (HEAT), a computer software program that can be

Table 1 | **Inventory Methodologies Included in This Paper**

Inventory name	Scale	Data requirements	Data collection method	Limitations
HEAT	City or county	VKT or fuel sales	Not specified	Ignores freeway traffic and trips that originate or end in other jurisdictions
CST-India	Metropolitan region	VKT, vehicle occupancy, emission factors	Travel surveys, assumptions	Poor data availability
San Francisco	City	VKT by trip type, transit emissions	Not specified	Attribution of emissions from transit trips might be inaccurate
COPERT	Can operate at multiple scales (city, metropolitan area, region)	VKT, vehicle fleet composition	Not specified	Does not include occupancy counts, cannot report per capita emissions
Portuguese model	City	Aerial imagery, GPS data, travel model	Aerial image tracking, GPS data collection, traffic counts, travel surveys	Does not include occupancy counts, cannot report per capita emissions
IVE	Can operate at multiple scales (city, metropolitan area, region)	VKT, vehicle fleet composition, activity data	Vehicle fleet composition, speed, vehicle technology, VKT, mode share	Uses data from only a small sample of roads and vehicles
World Bank	Can operate at multiple scales (city, metropolitan area, region)	Vehicle inventory, average fuel efficiency, VKT	Varies with location	Not intended for cross-city comparison
GEF	Metropolitan regional	Recent mode split, older mode splits, average trip distance by mode, vehicle fleet composition	Household travel survey or traffic counts	Does not provide a method for attributing emissions from trips that originate or end outside the boundary

accessed online to create comprehensive GHG emissions inventories for a jurisdiction, incorporating all the different activity sectors that generate emissions. The scale at which emissions are calculated corresponds to the geographic boundary of a city or county government. For the transportation sector, HEAT calculates emissions from passenger and freight transport, using county-specific emissions factors, applied to either VKT or fuel consumption data by vehicle type. HEAT considers all travel occurring within a specific geographical boundary and excludes all freeways.[40]

Depending on what fraction of travel within the city occurs on freeways, the emissions estimates provided by HEAT have varying degrees of accuracy. Furthermore, by only counting travel that occurs within the jurisdiction, the model ignores trips that do not occur entirely within the jurisdiction. Some trip segments are therefore attributed to localities that may not be able to implement policies to affect those trips, and that also have a responsibility towards those emissions.

CST-India estimates for transportation GHG emissions in three Indian cities

Scale	Metropolitan region
Data requirements	VKT, occupancy, emission factors
Data collection method	Travel survey, assumptions
Limitations	Poor data availability

Lisa Rayle and Madhav Pai of CST-India used available data on citywide travel patterns to estimate emissions from urban passenger transportation in three Indian metropolitan areas: Mumbai, Ahmedabad, and Surat.[41] The study used data from household travel surveys conducted in each city. The surveys, however, provided information only on the number of daily trips per person. The inventory therefore used assumptions for all the data not available to the researchers, such as travel distances, vehicle emissions, and mode share in each metropolitan region.[42]

Mode share assumptions were based on three scenarios, ranging from business as usual to gradual improvements to a sustainable urban transport system.[43] In the first scenario, “automobility ubiquity,” increased household wealth and availability of affordable vehicles lead to increased motorization rates, resulting in a decline in the use of two-wheeler vehicles. In the second scenario, “two wheeler world,” rising incomes combined with concerns over traffic congestion make motorcycles the most popular transport mode, while transit ridership remains high. In the third scenario, “sustainable urban transport,” policymakers promote sustainable transportation options, favoring public transit, walking, and biking.[44] Average trip distances were assumed to be a function of city size. The authors used existing data on average travel distances in each city (from travel surveys) and modified them based on the expected size of each metropolitan area in the future.[45] The inventory provided an estimate of total CO_2 emissions from urban passenger transport for each metropolitan area, expressed as total emissions (million tons CO_2/year) and total per capita emissions (kg CO_2/person/year), comparing 2005 to 2020 and 2040, under the three scenarios.

The goal of this study was not to develop an inventory for existing emissions per se in these metropolitan regions, but rather to forecast citywide emissions. While scenario modeling is conceptually distinct from an inventory, this example was included to illustrate the data quality and availability problems typical of developing world cities, which pose a major challenge to both forecasts and inventories. Forecasting emissions in the future, in addition to inventorying existing conditions, is well suited to the Indian context, where emissions are likely to change considerably over time due to expanding city sizes, rising incomes, and changes in mode share.

San Francisco citywide GHG emissions inventory

Scale	City
Data requirements	VKT by trip type, transit emissions
Data collection method	Not specified
Limitations	Attribution of emissions from transit may be inaccurate

The city of San Francisco is developing its own citywide transportation GHG emissions inventory, including emissions from passenger and freight transportation. Since San Francisco is part of the larger San Francisco Bay Area, including other major cities such as Oakland and San Jose, a large share of trips cross city limits. San Francisco is using different emissions measurement methods, depending on where trips originate and end. The inventory identifies three types of trips: those that occur only within San Francisco, those that originate or end in the city but also include segments in other cities, and those that only pass through San Francisco. The inventory proposes the following accounting methods for each category:

- Trips within San Francisco: VKT x GHG emissions/kilometer traveled;
- Trips partially within the city: 0.5 x VKT x GHG emissions/kilometer traveled; and
- Trips passing through: emissions are not counted

For public transit trips, the city uses different methods for the Muni system, which operates only within San Francisco, and the regional transit systems, such as the Bay Area Rapid Transit (BART) and Caltrain.[46] For Muni, the city reports total system-wide operating emissions. For the other transit systems, the following formula is used to estimate emissions:

(Total GHG emissions production of the transit system)
x
(boardings + alightings in San Francisco)/
(total system-wide boarding and alightings)[47]

Overall, the San Francisco inventory provides an accurate methodology for accounting for GHG emissions in a city that is part of a large urbanized region consisting of several medium to large cities. Emissions from regional transit trips are distributed between San Francisco and the rest of the Bay Area depending on the number of boardings and alightings in the city versus the rest of the system. In theory, this method could pose a problem if a large number of trains passed through San Francisco with few people getting on or off the train. In that case, the inventory would report low emissions from the trains, but in fact the trains would be running inefficiently, and there would be significant opportunities for increasing transit ridership on that line. In practice, because San Francisco stations have the highest number of passengers in the BART system, this is not the case.[48] However, if the inventory were to be applied to other cities that contribute fewer riders to the BART system, such as Richmond or Pleasanton, then the San Francisco method would be less accurate.

Computer Programme to calculate Emissions from Road Traffic (COPERT)

Scale	Can operate at multiple scales (city, metropolitan area, region)
Data requirements	VKT, vehicle fleet composition
Data collection method	Not specified
Limitations	Does not include occupancy counts, cannot report per capita emissions

COPERT, the Computer Programme to calculate Emissions from Road Traffic, is a software program designed to calculate air pollutant emissions from road transport. Its development has been coordinated by the European Commission’s Joint Research Centre and financed by the European Environment Agency. The software was designed for use in developing national emissions inventories, but it can also be used for citywide inventories. COPERT estimates GHG emissions as well as pollutants that affect local air quality from different vehicle types. The program calculates all these pollutant types and divides them into three types of emissions: 1) hot emissions (those produced during thermally stabilized engine operation), 2) cold-start and warming-up effects, and 3) fuel evaporation.[49] It also includes non-exhaust emissions related to tire and brake wear.[50]

The software user must input activity data, including population, annual mileage (km/year), mean fleet mileage for each vehicle type (km), average speed and mileage percentage driven by each vehicle type, fuel tank size, canister size, and percentage of vehicles equipped with fuel injection or evaporation control.[51] The software can then be used to calculate speed-dependent emissions factors and compile the emissions inventory. Since vehicle occupancy is not part of the methodology, it is up to the user to create estimates of emissions on a per capita basis, using the model results. The lack of occupancy data is problematic in that it cannot detect the effect of increased transit ridership or vehicle occupancy on emissions.

The Portuguese model

Scale	City
Data requirements	Aerial images, GPS data, travel model
Data collection method	Aerial image tracking, GPS data collection, traffic counts, travel surveys
Limitations	Does not include occupancy counts, cannot report per capita emissions

Gois et al. present a methodology for developing a very detailed inventory of traffic flow and emissions from transportation, and offer a case study of its application to the city of Lisbon, Portugal.[52] The model combines a bottom-up approach, in which traffic is allocated to each road link in the Lisbon street network, with a top-down approach that checks the total VKT resulting from the model against fuel sales data for the same period, which is used to calibrate the model results against the observed conditions. The model relies on counting vehicles in aerial photographs in order to determine the number of cars on each road link at a given moment in time. An additional step involves distinguishing moving cars from parked cars in aerial photos. It is not clear, however, that the aerial imagery can provide information on actual vehicle type. The number of vehicles is then added to each road link in a GIS file and, because some cars were equipped with GPS, researches were able to monitor speeds at each road link. The number of cars and travel speeds is then used to determine traffic flows. The model results are checked against actual traffic counts from more than 100 monitoring stations across the city to ensure that the model provides an accurate depiction of actual traffic conditions.[53]

The study used fuel emission factors from the EMEP/CORINAIR Emission Factor Handbook, as recommended by the European Environmental Agency. Each emission factor was represented as a non-linear regression curve, with vehicle speed as the independent variable, and included parameters such as engine size and incorporated emissions abatement technology by vehicle type.[54] As Lisbon is a major employment center, the study had to estimate emissions from numerous commute trips originating outside Lisbon and ending in the city center. In order to estimate the number of these trips, researchers conducted surveys of motorists at major entry points into Lisbon. One thing missing from this methodology, as in the COPERT model, is data on vehicle occupancy, which would allow the researchers to estimate total emissions on a per capita basis.

The International Vehicle Emissions (IVE) model

Scale	Can operate at multiple scales (city, metropolitan area, region)
Data requirements	VKT, vehicle fleet composition, activity data, emissions factors
Data collection method	Vehicle fleet composition, speed, vehicle technology, VKT, mode share
Limitations	Uses data from only a small sample of roads and vehicles

In order to estimate transportation emissions, many developing countries have relied on modified versions of US- or Europe-based models or emission factors. For example, Mexico and Hong Kong have tried to adapt EPA's Mobile Source Emissions Factor Model (MOBILE) and the California Emission Factors Model (EMFAC).[55] Adapting these models to a different location requires extensive changes. For example, these models use US-based vehicle emission factors, which cannot be applied to the vehicle fleet in a developing country. Some local governments, lacking the capacity to change models, have applied them directly, which led to significant errors in emission estimates.[56]

However, the IVE model is designed specifically for use in developing countries. IVE was jointly developed at the International Sustainable Systems Research Center and the University of California at Riverside as an easy-to-use modeling tool, relying on three types of inputs:

- Engine technology and add-on control distribution in the vehicle fleet;
- Driving behavior for different vehicle types on local roadways; and
- Vehicle emission factors specific to local vehicles.

The model includes a database of emission factors for vehicles ranging from two-wheelers to buses and trucks, compiled from data collected in the US, China, India, and Thailand. The goal was to achieve as much geographical variation in the data sets so that users could find a dataset that approximates their local context.

In case the users do not have information on the local vehicle fleet, they can choose a pre-loaded set of emissions factors for GHG emissions and other pollutants that most closely match the local fleet. This is an improvement over applying US- or Europe-based models directly. As the developers note, one of the recurring problems in developing countries is access to high quality data, and this is one of the most important challenges in creating an accurate emissions inventory.[57] In response to this challenge, the IVE researchers have developed a data collection methodology adapted to the data limitations in developing countries.

The World Bank citywide methodology transport module

Scale	Can operate at multiple scales
Data requirements	Vehicle inventory, average fuel efficiency, VKT
Data collection method	Varies with location
Limitations	Not intended for comparison of cities

In collaboration with internal staff and external institutional partners, the World Bank Carbon Finance Unit is developing a set of tools for estimating urban GHG emissions inventories across five sectors, including transport, as well as tools for estimating and monitoring emissions reductions associated with individual investments. The purpose of the methodology is to help cities leverage climate-based finance to support energy efficient, low carbon growth strategies.

The urban transport GHG emissions inventory component of the methodology will enable cities (and investors) to understand transportation's relative energy efficiency (or GHG emissions intensity) against other sectors, as well as to monitor performance of the sector over time.[58] Inventory results are normalized against a number of factors selected for each city, such as population, per capita gross domestic product, and national sector emissions. Since the purpose of the tool is to leverage finance, strong emphasis is placed on the transparency and audit trail of methods and results.

The urban transport inventory tool provides a menu of data collection options for the parameters used to calculate the inventory: an inventory of all vehicles in the study area, information on their activity level, and fuel efficiency. Each data collection option is based on an existing data collection method, accompanied by simple guidance for evaluating uncertainty in the data collected. Options are selected based on local data availability and the threshold level of uncertainty required by investors. To develop and refine the transport sector methodology, the Carbon Finance Unit hosts an open, on-going working group, in which EMBARQ participates.[59]

The draft Global Environment Facility manual for calculating GHG benefits of GEF projects

Scale	Metropolitan area
Data requirements	Recent mode split, past mode splits, average trip distance by mode, vehicle fleet composition
Data collection method	Household travel survey or traffic counts
Limitations	Does not provide a method for attributing emissions from trips that originate or end outside the boundary

The Global Environment Facility (GEF) has developed a draft step-by-step guide for inventorying GHG emissions from transportation at the metropolitan or regional level. The method compares a baseline (business-as-usual) case with a scenario including the GEF project, in order to assess potential GHG emission reductions for that project.

Data requirements for creating the inventory include a recent modal split and one or two older modal splits, preferably from five and ten years past, in order to have enough information to detect long term trends in mode shift. The method also requires data on average trip distance by mode and the mix of vehicle types in the fleet.[60] The GEF recommends that this data be collected from household origin-destination travel surveys. If those are not available, the best substitute would be vehicle and vehicle occupancy counts. The data can then be combined with emission factors for the vehicle fleet, calculated on a per-kilometer basis, in order to create a citywide or regional inventory of transportation GHG emissions.[61] The GEF inventory is intended for a region or metropolitan area where the GEF is implementing GHG emissions reductions projects. The inventory is meant to be updated annually, over the expected lifetime of the GEF project.

INTEGRATION WITH CLIMATE POLICY

California climate and transportation legislation

The California Senate Bill 375 (SB 375) is the first law in the United States that aims to reduce GHG emissions by curbing sprawl.[62] The goal of SB 375 is to reduce VKT through integrated transportation and land use planning, in order to achieve the GHG reduction goals set out in the Global Warming Solutions Act of 2006 (AB 32).[63] The law sets GHG reduction targets at the regional level, to be achieved from the automobile and light truck sectors for 2020 and 2035. Each MPO in the state is expected to prepare a "sustainable community strategy" aimed specifically at reducing VKT in the region.[64] The California Air Resources Board (CARB) has the responsibility to determine that each region is on track to meet its respective emission targets. In order for emissions inventories to be integrated with this process, the different citywide inventories would have to be aggregated at the regional level. City level inventories are useful to encourage cities to play their part in reducing regional transportation emissions. A citywide inventory is also more likely to pick up the effect of neighborhood-scale interventions, such as transit-oriented development.

US climate and transportation legislation

Establishing a standard or recognized methodology for US citywide transportation GHG inventories could support both climate and transportation legislation. The House-passed climate bill (HR 2454), Senate Environment and Public Works (EPW) Committee draft (S. 1733), and the Kerry-Lieberman discussion draft ("American Power Act") included extensive policy direction for reducing GHG emissions from the transportation sector, including a requirement for the EPA and Department of Transportation to work together to develop standard methodologies for inventories.[65] These three versions of the climate bill required GHG emissions inventories by regions (conducted by the MPO), not cities, and required state level reductions as well, a different geographical focus than many existing inventory methodologies. The advantage of doing inventories at a regional scale is that the geographic area of the inventory more closely approximates the travel or commute shed for the metropolitan area. This can increase the accuracy of data collection. For example, it would be easier to use fuel sales data to estimate total emissions, since most vehicles fueled within a large region will travel mostly within that same region. The main problem with using fuel sales data, however, is that it does not provide information on the underlying reasons for increases or decreases in emissions. As such, fuel sales data is more suitable as a validation tool for travel demand models.

The federal transportation authorization law presents similar issues, in part because the House-passed climate bill and Senate discussion drafts contained many elements that originated with Rep. James Oberstar's draft surface transportation authorization language. This draft would move the United States towards a performance-based approach to funding transportation projects, which, as noted above, would greatly benefit from a standard transportation emissions inventory methodology, if GHG emissions are one of the performance metrics. However, as noted with the climate bill, this draft reauthorization would send funds to states and MPOs, meaning that for performance measures to align with inventories, the inventory would need to assess regional or statewide transportation systems, rather than cities.

Since different levels of local and regional government have decision-making authority for projects and policies that might influence transportation GHG emissions, the challenge is how to create an inventory that could be easily and accurately aggregated from the city to the regional level, or disaggregated from the regional level to the city level. The methodology would have to allocate emissions to those entities that can influence them, and also allow data aggregation without double-counting or under-counting emissions. The trip-end attribution method would serve this purpose well for car trips, while the per-kilometer attribution method would be more suited for regional transit systems. Despite the challenges of creating a methodology to meet the needs of both cities and regions, it is an important next step if we want to encourage both citywide and regional reductions in transportation-related GHG emissions.

Integration with international climate policy

The Clean Development Mechanism (CDM) can be used by governments as an alternative to more expensive GHG emissions reduction projects in their own countries.[66] However, transportation has played a limited role in the CDM, due to difficulties in measuring GHG emissions reductions from small scale projects, the importance of behavioral changes in reducing transportion emissions and the additionality requirement (that the project could not be implemented but for the CDM funding) – all of which make evaluation difficult.[67] However, the TransMilenio Bus Rapid Transit system in Bogota, Colombia is a successful example of a transportation project that was approved under the CDM.

Some developing countries have agreed, under the Bali Action Plan, to undertake Nationally Appropriate Mitigation Actions (NAMAs). These are actions voluntarily proposed by developing countries to reduce GHG emissions below business-as-usual levels, in accordance with each country's capabilities.[68] NAMAs may be categorized into three groups: unilateral, supported, and credit-generating. The latter represent actions that could be credited for sale in the global carbon market after an agreed-upon crediting baseline has been reached. Huzienga and Bakker argue that NAMAs might be more promising for the transportation sector, due to their emphasis on policy interventions and co-benefits.[69] The ability to develop accurate transportation emissions inventories would be an important asset for including transportation projects under NAMAs. The inventory could help determine a business-as-usual baseline, and help obtain climate funding for transportation sector projects. It could be a useful tool for supported NAMAs, which could receive financial aid from the developed world, and potentially also for credit-generating NAMAs.

CONCLUSION

Choosing a transportation GHG emissions inventory methodology is a critical early step in developing a climate action plan or establishing transportation-related GHG emissions reduction strategies. Accuracy, sensitivity, precision, and attribution of an inventory method will determine how well it can inform these plans. The United Nations Framework Convention on Climate Change (UNFCCC) and Intergovernmental Panel on Climate Change (IPCC) guidelines indicate five quality criteria for emissions inventories: transparency, consistency, comparability, completeness, and accuracy. Ideally, an inventory will accurately:

- Depict the magnitude of transportation emissions, absolutely and relative to other sectors;
- Show the major contributors to local transportation emissions;
- Allow emissions to be calculated on a per capita basis;
- Inform the development of GHG emissions mitigation policies and projects; and
- Allow tracking of progress over time.

However, there is a significant tradeoff between accuracy and simplicity, and between comparability and sensitivity to minor changes. Navigating these tradeoffs is a complicated, yet unavoidable, exercise in choosing a methodology for a city, and even more so when trying to establish a standard methodology or one that can be used to compare results between and among cities.

Another major challenge is the difficulty in quantifying actual emissions reductions from any given policy or project.[70] An accurate inventory would help in defining a baseline of GHG emissions, as well as an estimate of the relative contribution of different factors to total transportation emissions. While it would not eliminate the uncertainty related to estimating the exact impact on emissions from specific projects, a detailed inventory would allow a better understanding of emissions-causing behavior and would suggest appropriate policies for reducing those emissions.

The main challenge in developing a citywide emissions inventory is dealing with the trips that cross city boundaries, including regional and long distance passenger trips, as well as the transport of goods and waste in and out of the city. This challenge can be addressed by developing an inventory at a regional scale. In this case, the boundary of the inventory area would more closely approximate the regional travel shed, and the issue of cross-boundary trips would be less important. But it is also important to develop the inventory at the scale of the local government body that has the authority to enact emissions reduction policies. A regional inventory makes sense where there is strong regional governance; however, in many metropolitan areas, cities still have greater authority than the regional government, making the citywide inventory a more effective tool for informing policy. While there are a number of methodological challenges raised here and elsewhere, creating inventories at any geographical level is a major step towards understanding – and mitigating – GHG emissions from the transportation sector.

NOTES

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