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GREEN HOUSE GAS EMISSIONS INDICATORS & APPROACHES

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Introduction

It is widely accepted that greenhouse gas (GHG) emissions are a major driving force behind global climate change, a phenomenon expected to cause potentially catastrophic impacts, such as temperature increases, drought, and a greater frequency of severe weather events (Parry et al, 2007). In the United States, transportation is the second largest emitter of GHGs (after the electric power industry) (PEW report), and emissions from this sector have grown considerably, accounting for nearly half of the 27 percent increase above benchmark (1990) levels observed nationwide by 2007 (Bhatt et al, 2010). Behind this trend are growth in vehicle miles traveled (VMT)[1], proportion of drivers traveling alone, average trip length, and trips per capita (Bhatt et al, 2010), all of which are responsible for increasing energy (fuel) consumption within the sector.

In the United States, transportation is the second largest emitter of GHGs (after the electric power industry), and emissions from this sector have grown considerably, accounting for nearly half of the 27 percent increase above benchmark (1990) levels observed nationwide by 2007.

Climate stabilization is an often stated goal, and would require the US to significantly reduce its GHG emissions. Specifically, policy discussions on both the international and domestic fronts have focused on limiting the global temperature increase to 2 to 3 degrees celsius by the year 2050 (Ewing, 2007). In order to accomplish this goal, national reduction targets from all sectors of up to 83 percent[2] – that's some 5,900 metric tons of GHGs annually – have been proposed (Cambridge Systematics, 2009).

Given the significant GHG contribution made by the transportation industry, it is clear that reductions in emissions from this sector will be instrumental in realizing the goal of limiting climate change impacts. Continued technological advances in the form of cleaner burning fuels and more efficient vehicles will help curtail emissions; however, a projected increase in VMT of 50% between 2005 and 2030 will undermine much of the total expected emissions reductions from these innovations (Ewing, 2007; Bhatt et al, 2010). In light of this reality, it is recommended that States identify, and work to accomplish, VMT or GHG reduction targets at the per capita level (Bhatt et al, 2010).

[1] VMT in the US increased by 151% between 1977 and 2001. (Bhatt et al, 2010)
[2] By 2050 as compared to 2005 levels. (Cambridge Systematics, 2009)

Define Indicators More Specifically

GHG emissions from the transportation sector result from an interplay of four factors: fuel efficiency of the vehicles on the road, miles traveled[3], carbon content of the fuel used to power those vehicles, and operational efficiency of vehicles during travel (EPA, 2012; Cambridge Systematics, 2009). Because of this, four general approaches are available to limit transportation-based emissions. To address the first two concerns, the efficiency of the fleet can be improved through advances in vehicle technology; or alternative fuels can be used which are characterized by a lower carbon content relative to traditional options. While promising, neither of these areas is primarily influenced by state-level policies or actions (Cambridge Systematics, 2009).

State policies can focus on:

- *Reducing overall miles traveled or switching to more efficient modes of travel*
- *Optimizing the transportation network's functioning*

Avenues more amenable to direct state action are alterations in travel activity and in vehicle and system operations. The former involves reducing the overall number of miles traveled, or shifting the means of transport to more efficient options. The latter, in turn, focuses on optimizing the transportation network's functioning, such that speed and traffic flow patterns result in highly efficient vehicle operations, which in turn, yield lower emission rates (Cambridge Systematics, 2009).

The US Departments of Energy and Transportation (DOE and DOT, respectively) engage in continual forecasting efforts to determine how anticipated industry innovations and existing federal regulatory mandates can be expected to impact the generation of GHGs by the transportation sector. DOE's "Annual Energy Outlook," for example, tracks yearly changes in vehicle and fuel technologies. DOT, in contrast, considers the expected trends resulting from the implementation of the Corporate Average Fuel Economy (CAFE) standards. Both agencies have concluded that expected technological innovations and the effects of more stringent standards will substantially reduce GHG emissions; these benefits, however, will be largely offset by anticipated increases in travel and in the US population as a whole (Cambridge Systematics, 2009).

Assuming baseline conditions prevail, the nation will still be 21 percent short of meeting its stated goal for 2020. The requisite additional reductions must therefore be accomplished through reduced VMT, increased utilization of more efficient travel means, and network optimization-focused actions.

Taking into account the DOE/DOT-determined "GHG emissions baseline," calculations have been conducted to quantify the reductions necessary to accomplish the goals set forth in the American Clean Energy and Security Act (HR 2454). These efforts underscore the important role of state-led transportation policies and actions in meeting

[3] Fuel efficiency and vehicle miles traveled are the inputs used to compute fuel consumption when employing a bottom-up approach.

the emissions limits set forth in the Act for 2012, 2020, 2030 and 2050. Simply put, assuming baseline conditions prevail, the nation will still be 21 percent short of meeting its stated goal for 2020 (Cambridge Systematics, 2009). The requisite additional reductions must therefore, be accomplished through reduced VMT, increased utilization of more efficient travel means, and network optimization-focused actions.

Given the clear relationship between policy decisions designed to impact travel behaviors and/or network efficiencies and the generation of GHGs, there can be no question that utilizing an emissions-focused indicator to help gauge project and policy effectiveness is appropriate and highly beneficial. There are a number of emissions-related indicators from which States can choose, however, and the specifics (i.e. advantages and disadvantages, sensitivity, data needs, etc.) of each are discussed here.

Top-Down vs. Bottom-Up GHG Emissions and Fuel Consumption Calculations

The first use of a GHG inventory to track emissions occurred in conjunction with the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. In that same year, the US EPA initiated its State and Local Climate Change Program (SLCCP), intended to facilitate actions at these levels focused on GHG emissions reductions. The SLCCP encourages states to prepare their own inventories, and the vast majority have done so, including transportation emissions as a standard component (Gallivan et al, 2008).

Although easy to calculate, one of the most basic limitations of a fuel sales-based metric for approximating GHG emissions is the very real possibility of a spatial mismatch between the amount of fuel sold in a state and the amount consumed there.

GHG emissions can be calculated using either a "top-down" fuel-based approach, or a "bottom-up" technique, largely based on VMT . Emissions inventories at both the national and state levels are often based on fuel consumption (by fuel type), a top-down reporting mechanism that relies on fuel sales data, and is appealing due to the ease with which it can be calculated. Specifically, for most state inventories fuel consumption is estimated from the US Energy Information Administration's State Energy Consumption, Price, and Expenditure Estimates; fuel tax records; or state energy estimates (Gallivan et al, 2008).

As described in greater detail below, for CO_2 calculations, the conversion from gallons of fuel sold[4] to transportation emissions is straightforward. In contrast, N_2O and CH_4 cannot be determined directly using a conversion rate (their calculation requires information on fleet composition and activity), but the necessary inputs are readily available (Gallivan et al, 2008).

Although easy to calculate, one of the most basic limitations of a fuel sales-based metric for approximating GHG emissions is the very real possibility of a spatial mismatch between the amount of fuel sold in a state and the amount consumed there. A recent study, for example,

[4] Gallons of fuel sold is often used as a proxy for fuel consumption at the state level.

found that a significant proportion of the fuel consumed in New York State was purchased in neighboring New Jersey. In this case, the emissions inventory for the former state would be too low if based on fuel sales data, while the latter would be too high if this methodology were used (Gallivan et al, 2008).

A top-down approach also suffers from an inherent lack of specificity. Results are not typically reported by individual modes or vehicle types - information which can be important in informing policy decisions, and is easily understood by members of the public – but are instead related according to fuel types consumed (typically gasoline, diesel, and jet fuel). Emissions totals can be disaggregated to yield more detailed information (for example, emissions from light-duty vehicles as opposed to freight traffic) but this process of "backing out" from totals to specific emissions sources is known to introduce errors resulting from the assumptions and inaccuracies inherent in the VMT figures for different vehicle types, discrepancies between the fuel economy data available for the nation as a whole and the fleet characteristics of a particular state, and the differences that exist between fuel sales and fuel consumption statewide (Gallivan et al, 2008).

Due to the potential for differences between fuel sold and consumed within a state, as well as the need for a greater level of specificity related to vehicle types to both inform and test the effects of various policy decisions, a bottom-up approach to emissions inventorying may be desirable. Such methodologies also mesh well with ongoing transportation modeling activities at the state and/or metropolitan planning organizational (MPO) levels, which typically estimate (among other things) fuel consumption and VMT (Gallivan et al, 2008), and may calculate emissions totals on a more or less regular basis (EPA, 2012).

Generically speaking, bottom-up approaches to calculating on-road emissions rely on information related to in-state VMT (broken down by vehicle and fuel type) and fuel efficiency (also by vehicle and fuel type)[5]. Taken together, these data can be used to determine gasoline and diesel consumption by vehicle type; which, with the application of emissions factors, yield individual emissions totals for light- and heavy-duty gasoline and diesel vehicles (EPA 2012; Gallivan et al, 2008). Total statewide emissions from transportation can then be determined by aggregating across categories.

Keeping this background information in mind, specific approaches for calculating GHG emissions and related indicators are presented below, followed by a set of recommended future actions related to indicator development and use.

Travel Demand Models

Travel demand models (TDMs) developed for use by states, MPOs, and other localities manipulate a variety of very specific data points to forecast traffic, evaluate transportation system operations, and test alternative transportation policies and investments. TDMs are often employed in assessing transportation emissions, and can output VMT (discussed in greater detail

[5] Fuel consumption is calculated at the product of these two inputs.

below) estimates under a variety of scenarios, making them integral to bottom-up methodologies of GHG inventorying (Gallivan et al, 2008; KYDOT, 2012).

Depending on the scope and purpose of a TDM, data needs vary; but typically, 5 types of information are used to populate a model of this kind. Measures of traffic volume and vehicle classifications are necessary from throughout the study area. Population and employment statistics are combined to predict travel at the zonal level and future trips. Projections of future land use are also important, as are measures of travel behavior. Finally, geometric and operational highway data are needed to construct models for locales where highways exist (KYDOT, 2012).

Data sources vary, but may include household travel and origin-destination surveys, transit system maps and flows, traffic and passenger counts, and land use plans and models (KYDOT, 2012). In some circumstances, data collected by the Federal Highway Administration's Highway Performance Monitoring System (HPMS) may be useful for populating such models, as it tracks measures including land area and population, VMT on some public roads, and the percentage of miles traveled by vehicle type (GAO). The utility of the HPMS may be limited, however, by the fact that comprehensive data are not available for all measures at all scales for all locations (USDOT, 2012).

A variety of software platforms, such as MinUPT and TransCAD, can be employed to construct TDMs (KYDOT, 2012). Typically, outputs are determined through a four step process. The amount of travel to and from specific locations is calculated, and these rates are used to predict trips. Once calculated, trips are assigned to the various modes and vehicle types available (Gallivan et al, 2008).

Despite the fact that inaccuracies in local fleet information may introduce errors into demand model outputs, as well as their limited ability to predict changes in heavy duty traffic due to the influence on these vehicles of factors beyond such models' scopes, travel demand models developed by MPOs and others are generally thought to provide the most accurate VMT estimates available (Gallivan et al, 2008). Root mean square error (RMSE), VMT by functional class, and screenlines are measures commonly used to assess the accuracy of a given TDM by comparing existing traffic volumes with model predictions, and only very small margins of error are tolerated (KYDOT, 2012).

> Travel demand models developed for use by states, MPOs, and other localities manipulate a variety of very specific data points to forecast traffic, evaluate transportation system operations, and test alternative transportation policies and investments.

TDMs are not without their shortcomings. Models of this kind may not be able to capture the impacts on VMT of all possible reduction strategies. Reductions due to improvements to bicycle and pedestrian amenities, or geographically-limited land use changes, for example, may not be reflected in their outputs. What's more, many models do not include local roads, which typically account for between 5 and 20 percent of VMT in a metropolitan area. In such instances, additional estimates must be conducted and added to model outputs to surmise total VMT (EPA, 2011).

Not all locations are covered by existing TDMs, and the process of creating a new TDM can be quite expensive, as well as labor and time intensive (EPA, 2011; KYDOT, 2012). A number of state-level TDMs have already been developed, but only about half appear to use their models to inform long-range transportation planning efforts (GAO). States that have yet to create comprehensive TDMs typically rely heavily on population growth estimates to determine VMT, omitting important considerations such as policy decisions and infrastructure investments. Obviously, the relatively small scale of non-DOT generated estimates is problematic when a state-wide picture of VMT is desired, and upscale and/or the combination of multiple models covering various areas of a single state may be difficult (Gallivan et al, 2008).

Data type	Data Source
Traffic volume	Traffic and passenger counts, Federal Highway Administration's Highway Performance Monitoring System (HPMS)
Vehicle classifications	Vehicle registration data, and depending on the level of specificity of the model, bus companies, transit agencies, school districts, refuse haulers, and local governments
Population	US Census, Federal Highway Administration's Highway Performance Monitoring System (HPMS)
Employment	Bureau of Labor Statistics
Land use projections	Local planning departments, Departments of Environmental Protection (and similar)
Travel behavior	Household origin and destination surveys

Advantages	Disadvantages
TDMs already exist at the MPO and other sub-state levels	Existing models likely differ in specification, data sources, and other important characteristics
Known to produce good estimates of VMT and other outputs that can serve as indicators	Data intensive to create and run
	Not all areas and/or road types are modeled
	Ability to reflect impacts of small changes is limited
Can forecast the effects of policy and investment options	Inaccuracies may arise as a result of poor data inputs or poorly specified models

At what scale can TDMs be used?

Some states have more or less comprehensive TDMs, but these are typically not used for long-term forecasting. Most commonly, TDMs are developed for the MPO or other sub-state level, and although it may be possible to combine outputs from multiple models to represent larger geographic regions, differences in model specifications may complicate such an effort.

Regardless how similar different TDMs are, they will likely not provide coverage for an entire state, necessitating mathematical extrapolation, temporary traffic counts, and other measures if a full, statewide picture is desired. Alternatively, output from existing TDMs could be tracked in a central location to determine overall trends within a state without undertaking a new modeling effort. The option of creating a new statewide TDM, while not impossible, would likely prove very resource intensive.

Vehicle Miles Traveled (VMT)

VMT is a measure of the number of miles traveled over a specified time period, and is most often calculated using a TDM. Not only is VMT an important metric in and of itself, it is also used to calculate a variety of other road-related measures, including traffic fatalities, fuel efficiency, and emissions (St. Denis, 2011). The link between VMT, congestion, and GHG emissions is fundamental and positive in its direction[6]; hence, reducing VMT is integral to addressing climate change concerns (EPA, 2011).

Because of continued population growth and economic development, many states may wish to focus on achieving reductions per capita, rather than total VMT. One approach is to model VMT for all vehicle activity; however, since heavy-duty vehicle activity is not typically influenced by demand management strategies to the same degree as that of its light-duty counterparts, it may be advisable to focus analyses on the latter as a means of gauging the effectiveness (or potential effectiveness) of such actions (EPA, 2011).

There are a number of factors that make VMT an appealing metric by which to measure the success of GHG emissions reductions-focused efforts. Because VMT does not take into account vehicle fleet characteristics or the carbon content of the fuel burned, alterations in vehicle technologies or gasoline and diesel formulations would not influence performance tracking efforts. The fact that transportation planning and other agencies involved in designing and implementing climate change mitigation-based policies and projects can exercise direct influence over VMT, but not over marketplace innovation further underscores the inherent value of this measure (EPA, 2011).

Drawbacks associated with relying on VMT as a proxy for measuring GHG emissions are numerous, however. A number of non-VMT dependent factors influence emissions. For example, fuel economy, the carbon content of fuels, and the efficiency with which the transportation system operates, are all key determinants of overall emissions. What's more, monitoring VMT will not capture changes in GHGs due to improvements in transportation system management and operations strategies. Lower speed limits and improvements to traffic signal operations and incident management approaches that reduce traffic delays are all known to lower emissions, but will not impact VMT calculations (EPA, 2011).

In addition to acting as key input for bottom-up approaches to GHG inventorying, VMT per capita can sometimes be used as a proxy for CO_2 emissions per capita (discussed below).

[6] Increases in VMT lead to increases in congestion and emissions.

Specifically, in circumstances where average fuel economy and fleet and fuel mixes are relatively consistent, such an approach is viable because the relationship between VMT and CO_2 emissions at the individual level is essentially linear (EPA, 2011).

There exist a number of conditions under which per capita VMT is a poor proxy for CO_2 emissions, however. When improvements in fuel economy are anticipated –such as those resulting from innovations in vehicle technologies or fleet composition, or from traffic-smoothing-focused measures – the VMT/ CO_2 relationship breaks down. Similarly, changes in fuel composition can alter per gallon emissions rates. Finally, when passengers shift from personal vehicles to another mode of travel (for example, buses or rail), or freight is moved more by train than truck, VMT is no longer a reliable stand-in for CO_2 emissions (EPA, 2011).

Calculating VMT

Using Fuel Sales Data:

$$VMT = (Ret_{sales} \times MPG) / PPG \quad (2\text{-}1)$$

where:

Variable Name	Data	Data Source
Ret_{sales}	total fuel sales (in dollars) for the study area	US Energy Information Administration's State Energy Consumption, Price, and Expenditure Estimates; fuel tax records; or state energy estimates
PPG	average unit price per gallon of fuel in dollars	US Energy Information Administration's State Energy Consumption, Price, and Expenditure Estimates; fuel tax records; or state energy estimates
MPG	fleet fuel efficiency in miles per gallon	National data: US EPA, State-specific data (not available in all states): State DOTs

Advantages	Disadvantages
Calculation is arithmetically straightforward and easy for a non-technical audience to understand	Mismatch between fuel purchase and fuel use may lead to inaccuracies, especially in small study areas and study areas near state borders
Data are readily available	The availability of state-specific fleet characteristics may be limited

Using Traffic Count Data:

VMT = ∑(AADT x RSL) for all roadway sections within the study area

Where:

Variable Name	Data	Data Source
AADT	Average Annual Daily Traffic	State DOT/MPO-conducted traffic counts (long-term, permanent continuous counts; short-term portable counts; and/or special needs counts)
RSL	Roadway Section Length	State DOTs, MPOs, GIS (US Census' Tiger Streets, etc.)

Advantages	Disadvantages
Relies on actual, observed traffic flows, rather than a proxy measure	Traffic counts are not available for all roads (rural/smaller roads, in particular, are unlikely to be counted) – as a general rule of thumb, such sections contribute about 20% to overall VMT, but the accuracy of this generalization varies considerably from one locale to another
MPOs and others already possess these data and in many cases counts are continuous, facilitating trend tracking	All vehicles counted are assumed to travel the length of the road section (which they may not), and vehicles that enter and exit a road without passing a data collection point are omitted
Calculation is arithmetically straightforward and easy for a non-technical audience to understand	

To calculate per capita VMT, the totals determined using the above approaches can be divided by the study area's population. Population data are available from the US Census through their American FactFinder web portal.

Fuel Consumption

GHGs are generated through the combustion of fuels, therefore, monitoring fuel consumption levels can provide insights into the effects of policies and investments designed to curtail emissions. This approach may be particularly appealing when the impacts of actions aimed specifically at reducing fuel consumption (e.g., a new or increased fuel tax) are undertaken.

Fuel sales data – obtained from the Federal Highway Administration's Office of Highway Policy Information's Highway Finance Data Collection, the U.S. Energy Information Administration's State Energy Consumption, Price, and Expenditure Estimates, or state fuel tax records or energy estimates – can be used as a proxy for use. However, with all such approaches, the mismatch between where fuel is bought and where it is used can prove problematic.

To avoid the potential errors resulting from a top-down calculation, fuel consumption can be calculated as the product of state (or other analytical level) VMT and the fuel efficiency of the local fleet. Alternatively, models such as EPA's MOVES can be set to output this measure.

Fuel consumption data are an input in bottom-up GHG calculations of the type discussed throughout this report. It may be possible, therefore, to monitor fuel consumption in conjunction with GHG-focused tracking efforts.

Advantages of Tracking Fuel Consumption	Disadvantages of Tracking Fuel Consumption
Can be tracked easily using fuel sales data as a proxy (i.e. a top-down approach)	Top-down calculations can suffer from a spatial mismatch between fuel sales and consumption.
Fuel consumption is an input variable for other, GHG-focused calculations, and may therefore be available from existing sources.	Fuel consumption levels may not change appreciably in response to small-scale land use changes.
Fuel consumption could be an ideal metric for testing the impacts of policies and investments (such as new or increased gas taxes) aimed directly at influencing people's fuel usage	Potential reductions in fuel consumption levels resulting from policy and investment decisions may be offset by population growth and continued urbanization in some areas.

<u>Calculating Fuel Consumption:</u>

Using Fuel Sales:

FC=FS

Where:

Variable Name	Data Description	Data Source
FS	Fuel sold in gallons	Office of Highway Policy Information's Highway Finance Data Collection, US Energy Information Administration's State Energy Consumption, Price, and Expenditure Estimates; fuel tax records; or state energy estimates

Advantages of Using Top-Down Approach at the Individual State Level	Disadvantages of Using Top-Down Approach at the Individual State Level
Easy to calculate	Will only reflect impacts of policy decisions and/or investments that directly impact fuel sales
Not resource-intensive to apply	Spatial mismatch between fuel sales and consumption can lead to inaccuracies.

Advantages of Using Top-Down Approach TCI-Wide	Disadvantages of Using Top-Down Approach TCI-Wide
Easy to calculate	Will only reflect impacts of policy decisions and/or investments that directly impact fuel sales
Not resource-intensive to apply	
Spatial mismatch between fuel sales and consumption would be minimized to do large area	

Using Efficiency and VMT (Bottom-Up):
FC=AFExVMT

Where:

Variable Name	Data Description	Data Source
VMT	Vehicle miles traveled is a measure of the number of miles traveled over a specified time period.	Travel Demand Models, Traffic Counts (see above)
AFE	Average fuel economy is the average miles per gallon traveled by vehicles on the road.	EPA has national data, state DOTs may have data that are more locally representative

Advantages of Using Bottom-up Approach at the Individual State Level	Disadvantages of Using Bottom-Up Approach at the Individual State Level
Does not suffer from spatial mismatch between fuel sales and consumption	Data on VMT and AFE is unlikely to be available for a whole state, and data that are available for individual locales may differ in ways that may make it difficult to input them into a single calculation.
VMT data may be available from MPOs and other sources	VMT is the only input over which states have an appreciable amount of control.

Advantages of Using Bottom-up Approach TCI-Wide	Disadvantages of Using Bottom-up Approach at the Individual State Level
National AFE data are more likely to be representative of the TCI region than they are of any individual state.	Local data on VMT and AFE is unlikely to be available for all areas, and data that are available may differ in ways that may make it difficult to input them into a single calculation.

CO_2 Emissions

Carbon Dioxide (CO_2) is the primary GHG, and accounts for about 95% of the transportation sector's contribution to climate change (EPA, 2011). It is a direct product of the combustion of fossil fuels, meaning that unlike conventional air pollutants, its levels in vehicle exhaust cannot be lowered using catalytic converters, oxygen sensors, or onboard computers. Every gallon of fuel used in transportation generates about 20 pounds of CO_2 emissions, and to date, the only way states can work to curtail its production is to reduce gasoline and diesel fuel use (Ewing et al, 2007).

"Carbon Intensity" (CI) is one EPA recommended measure of CO_2 production, and represents per capita CO_2 emissions resulting from transportation. CI can be calculated for multiple modes, or individual modes of transportation, but is most often specified as either CO_2 emissions for all transportation, passenger transportation alone, or heavy duty vehicles alone.[7] The motivation for distinguishing between passenger and heavy duty vehicles reflects the reality that the latter is somewhat inelastic as compared to the former, meaning that the effects of policy and/or regulatory transportation-focused actions may produce more limited effects.

CI is best used to track the effectiveness of activities related to long-range transportation planning, programming, land use visioning, and performance monitoring, and is most useful when applied at the regional scale, as transportation projects can be expected to impact carbon intensity beyond their geographical boundaries (EPA, 2011).

In addition to (or in lieu of) CI, total CO_2 emissions can serve as an indicator of progress toward reducing transportation's contribution to climate change at the State or other level. The benefit of tracking total CO_2 emissions is that such a measure speaks directly to progress toward accomplishing absolute reductions in GHG production. CI, on the other hand, reflects changes in CO_2 production at the level of the individual, making it possible to gauge individual behavioral modifications that might not be evident using a cumulative metric due to expected increases in population size. The conversion between total CO_2 emissions and CI is simple, making the tracking of both a straightforward endeavor.[8]

CO_2 emissions can be estimated using one of two bottom-up approaches, both of which rely on VMT as an input. A simple formula exists for this purpose: CO_2 equals VMT divided by average fuel economy (measured as miles per gallon) times carbon content of fuel (measured as grams per gallon). Depending on the data available for analysis, this equation can be adapted to provide emissions for individual vehicle classes and modes. Alternately, travel demand inputs can be entered into emissions models, such as EPA's MOVES (discussed in detail below), which output CO_2 estimates in addition to the levels of other GHGs resulting from transportation (EPA 2012).

[7] Personal vehicles accounts for some 60 percent of transportation related emissions; freight trucks, in turn, generate another 20 percent (Bhatt et al, 2010).

[8] To determine total CO2 emissions from CI, multiply CI by population. Conversely, to determine CI from the total CO2 emissions, divide total CO2 emissions by population.

Emissions of CO_2 can also be calculated using fuel sales data, in which case the amount of fuel sold is multiplied by a carbon content coefficient specific to the fuel type in question, the portion of the fuel oxidized (usually assumed to be 100% for on-road emissions), and a ratio of the molecular weight of CO_2 to the molecular weight of carbon (44/12).

Advantages of Tracking CO_2 Emissions	Disadvantages of Tracking CO_2 Emissions
Most important GHG	CO_2 is not the only GHG of concern
Is not impacted by vehicle technologies but can be influenced by state policies	
Direct relationship between gallons of fuel consumed and production	

<u>Calculating CO_2 Emissions:</u>

Using Fuel Sales (Top-Down):

$CO_2 = F \times CC \times (44/12)$

Where:

Variable Name	Data Description	Data Source
F	Fuel sold in gallons	Office of Highway Policy Information's Highway Finance Data Collection, US Energy Information Administration's State Energy Consumption, Price, and Expenditure Estimates; fuel tax records; or state energy estimates
CC	Specific carbon coefficient for the fuel type under study	EPA

Advantages of Using Top-Down Approach at the Individual State Level	Disadvantages of Using Top-Down Approach at the Individual State Level
Easy to calculate	Will only reflect impacts of policy decisions and/or investments that directly impact fuel sales (and CC, although this is not under direct state control)
Not resource-intensive to apply	Spatial mismatch between fuel sales and consumption can lead to inaccuracies.

Advantages of Using Top-Down Approach TCI-Wide	Disadvantages of Using Top-Down Approach TCI-Wide
Easy to calculate	Will only reflect impacts of policy decisions and/or investments that directly impact fuel sales (and CC, although this is not under direct state control)
Not resource-intensive to apply	
Spatial mismatch between fuel sales and consumption would be minimized to do large area	

Using VMT (Bottom-Up):
CO_2 = VMT/(AFE x CC)

Where:

Variable Name	Data Description	Data Source
VMT	Vehicle miles traveled is a measure of the number of miles traveled over a specified time period.	Travel Demand Models, Traffic Counts (see above)
AFE	Average fuel economy is the average miles per gallon traveled by vehicles on the road.	EPA has national data, state DOTs may have data that are more locally representative
CC	Carbon content of fuel is the percentage of the gasoline and diesel fuels on the market that is composed of carbon (which will be transformed into carbon dioxide when combusted). Carbon compositions of fuels change in response to the addition of ethanol and other substances to their formulations.	EPA

Advantages of Using Bottom-up Approach at the Individual State Level	Disadvantages of Using Bottom-Up Approach at the Individual State Level
Does not suffer from spatial mismatch between fuel sales and consumption	Data on VMT and AFE is unlikely to be available for a whole state, and data that are available for individual locales may differ in ways that may make it difficult to input them into a single calculation.
	VMT is the only input over which states have an appreciable amount of control.

Advantages of Using Bottom-up Approach TCI-Wide	Disadvantages of Using Bottom-up Approach at the Individual State Level
	Data on VMT and AFE is unlikely to be available for all areas, and data that are available may differ in ways that may make it difficult to input them into a single calculation.

EPA's Motor Vehicle Emissions Simulator (MOVES)

EPA's MOVES is a sophisticated, data-intensive bottom-up methodology, which recently replaced the Agency's MOBILE model. MOVES combines travel activity estimates and emissions factors, to predict transportation-generated GHG emissions and estimate energy consumption for time periods between 1990 and 2050 (EPA, 2001 and 2012). Specifically, the model includes vehicle types, ages and operating modes (running, start, and idle), which are represented by precise emissions factors. These factors are multiplied by measures of vehicle activity (i.e. VMT, vehicle starts) to produce the model's output (EPA, 2012).

In many instances, MOVES' predictions track closely with those produced using a top-down methodology; however, users of MOVES will realize a number of advantages relative to other, cruder approaches, many of which are of particular importance when the impacts of specific policy and investment decisions are of interest (EPA, 2001). The impacts of regional strategies on travel demand (such as rideshare programs) can be estimated using MOVES, as can smart growth initiatives. The anticipated effects of pricing strategies (including mileage or increased parking fees) can also be predicted using this model. MOVES can also be employed to predict the effects of efforts to increase transit ridership (EPA, 2012).

In general, MOVES estimates are believed more precise than those derived through fuel sales alone. This is because information related to future fleet characteristics is incorporated into calculations, as are predicted alterations in driving patterns (EPA, 2001 and 2012).

> MOVES allows users to specify inputs to represent possible investment alternatives, for example, thereby facilitating comparisons between possible future scenarios, thereby better informing the planning process than a top-down approach

Unlike emissions inventories calculated using fuel sales, MOVES estimates are not skewed by the spatial mismatch between fuel sold and fuel used in a given state. Greenhouse gases in addition to CO_2 are estimated by this EPA-developed approach; and because the model is already in use in some states as a way to ensure State Implementation Plan (SIP) conformity, in many jurisdictions it could be applied for GHG emissions calculations with minimal additional effort (EPA, 2011).

MOVES is not a forecasting panacea, however; the main drawback of this approach is the specificity of the data required to create accurate and reliable estimates. The model comes populated with generic values for many of the variables, but it is strongly suggested that verified local data are used whenever they are available to ensure the most precise outputs.

At a minimum, the EPA recommends inputting VMT and vehicle population data at the local scale. Information about a state's vehicle population can be obtained from vehicle registration records, and historic VMT is available from the FHWA's Highway Performance Monitoring System. Future VMT can be determined using a travel demand model (discussed above), by applying a growth factor to historic VMT figures, or by using a sketch or micro-simulation model (EPA, 2001).

MOVES is quite flexible with regard to data outputs. The model can calculate emissions as either an "inventory" (total emissions for the time period expressed in units of mass) or "emission rates" (expressed as emissions per vehicle for starts and extended idle emissions, or per unit of distance traveled). The user has many options with regard to the time period under consideration. Emissions can be determined on a daily basis, throughout the course of a calendar year, or over virtually any other time period that could be useful in informing the decision making process or gauging progress toward climate change mitigation goals. The scale at which analyses are focused is also malleable, with possibilities ranging from as small as the county level, to as large as a metropolitan, state, or even national focus (EPA, 2011).

When specifying the area of analysis, users can make use of a "county" or a "custom" domain. The former requires the most specific data inputs, and can be run either for a single county or multiple times for different jurisdictions, producing data which can be summed across areas to create a single, holistic picture of a multi-county locale. By selecting a custom domain, users can create an emissions profile for a multi-county area in a single run. While faster and less data-intensive than summing multiple county-level outputs, this approach does not afford as high a level of specificity as the former, because inputs assume single values throughout the area under analysis (EPA, 2011).

Advantages of Moves	Disadvantages of Moves
Detailed GHG-related outputs	Default data may not be representative of study area
Forecasting impacts of policy and investment decisions is possible	Data intensive methodology
Flexible with regard to scale and timeframe of analysis, as well as output type	
Does not suffer from spatial mismatch between fuel sales and consumption	

Running MOVES:

The MOVES program can be downloaded from the EPA's website, and webinars and one-on-one assistance are provided by the Agency. The calculations performed by the model are too complex to detail here, but data needs and sources are outlined below.

Data Type	Description	Data Source(s)
Meteorology	Temperature (in degrees Fahrenheit) and relative humidity (percentage) are needed for each hour of the timeframe over which the model is run – these numbers can be estimated using an EPA tool that	National Climatic Data Center

	converts daily highs and lows into hourly figures.	
Source Type Population	MOVES requires population data for 13 source types (motorcycle, passenger car, passenger truck, light commercial truck, intercity bus, transit bus, school bus, refuse truck, single unit short-haul truck, single unit long-haul truck, motor home, combination short-haul truck, and combination long-haul truck).	Vehicle registration data, bus companies, transit agencies, school districts, refuse haulers, local governments. Population data that cannot be obtained directly from these sources can be estimated by manipulating the MOVES model.
Age Distribution	Distribution of vehicle ages within the study area's fleet. This can vary widely from place to place, but it is generally accepted that the overall distribution remains more or less the same through time as old vehicles are retired and new ones brought in to replace them. This anticipated consistency allows for future emissions and fuel consumption to be estimated by inputting current fleet age characteristics into MOVES.	Vehicle registration data. Age distribution data may have already been compiled for SIP and conformity purposes. EPA has also created converters to transform registration distribution input files for MOBILE6.2 or NMIM into vehicle age distributions. MOVES default data may be used, although it reflects the national average and may not be representative of the study area.
Vehicle Type VMT	Miles traveled by all vehicle source types over all road types on an hourly basis for the time period being analyzed. This highly specific measure is accomplished by entering annual VMT by vehicle type for the year under study (the only component for which no default data exist within the model)., If more detailed information is known related to travel patterns it can be entered, or default settings can be used.	Travel demand models, local count data.
Average Speed Distribution	Distance traveled (in miles) divided by travel time (in hours). Because this measure includes all vehicle operations (including stopping at intersections, and other slowdowns) it will be less than the posted speed limits.	Post-process data from travel demand models
Road Type Distribution	The amount of miles traveled by each vehicle type over various road types	EPA-developed VMT converters
Ramp Fraction	Percentage of roads that consist of ramps	Default (8%) may be used, or location-specific data if available as part of existing travel demand models.
Fuel	Fuel formulation supply information	Default data are usually best, but if local volumetric fuel property information is available, it should be used.
I/M Programs	Inspection and maintenance data are only required when modeling methane emissions (not for CO_2, N_2O, or elemental carbon).	The same data used for SIP and conformity purposes should be included in MOVES.

Advantages of Using Moves at the Individual State Level	**Disadvantages of Using Moves at the Individual State Level**
Default values and EPA-developed converters exist to help populate the model when local data are not available.	Very data intensive
Avoids spatial mismatch in fuel sales vs. use possible when using top-down approach	Depending on scale and type of analysis specified, server time needed to run the model can be considerable.
Forecasting capacity allows user to test impacts of various investment and policy decisions	Default values reflect national averages and may not be representative of smaller study areas.
Model inputs are detailed enough to reflect the effects of many (but not all) smaller-scale efforts.	Effects of localized efforts, particularly those aimed at bicycle and pedestrian-oriented improvements, may not be captured.
Study scales can be specified at various levels, making this model amenable to application at local, county, state, regional, and national levels.	Many variables in runs conducted for areas above the county level must assume a single value, thereby losing some degree of accuracy.
Is already in use in many states for SIP and conformity purposes	
Model is available free of charge and technical assistance is provided by EPA	

Advantages of Using MOVES TCI-Wide	**Disadvantages of Using Moves TCI-Wide**
Would provide a detailed description of GHG emissions	Data intensive
Could facilitate multi-state planning efforts	Study area specification would have to take the form of the less detailed "custom" domain, as utilizing a "county" domain would be prohibitively resource intensive.
Because of large spatial extent, default values would likely be more representative of the TCI region than of any individual states.	

Recommendations

The table below briefly summarizes the appropriateness of the indicators outlined throughout this paper for use at the sub-state, statewide, and TCI-wide scales

Recommended Approaches at the Sub-State, State and TCI-Wide Levels			
Method	**Preferred for Sub-State Level Analyses**	**Preferred for State-Level Analyses**	**Preferred for TCI-Wide Analyses**
Travel Demand Models	✓	✓	
Vehicle Miles Traveled (Top-Down)			✓
Fuel Consumption		✓	✓
Vehicle Miles Traveled (Bottom-Up)	✓	✓	
CO2 (or CI) Emissions (Top-Down)			✓
CO2 (or CI) Emissions (Bottom-Up	✓	✓	
MOVES	✓	✓	

Given the variations between TCI-participating states in terms of current conditions and desired outcomes, there is likely no "one size fits all" course of action. The table below outlines a series of possible scenarios by which states interested in utilizing an indicator to track GHG emissions might go about accomplishing this.

Options at the State Level		
Current State	**Desired State**	**Recommended Action**
Good and consistent local data from MPO (and other) TDMs, few resources at state level for measuring GHG emissions	Track GHG-reduction progress in key locations	Amass model outputs from existing TDMs and use them to calculate emissions of either CO_2 (or CI) or all GHGs for the areas they represent using the model that best suits existing capacity

		and resources. Repeat this process on an annual basis (or more frequently) to measure trends.
	Track GHG-reduction progress statewide	Use fuel sales data to calculate CO_2 (or CI) emissions statewide. If possible, gather results of more resource intensive (i.e. bottom-up) analyses from neighboring states to determine whether a spatial mismatch between fuel sales and consumption may exist. If mismatch exists, determine its magnitude and adjust finding accordingly. Repeat this process on an annual basis (or more frequently) to measure trends.
Good and consistent local data from MPO (and other) TDMs, sufficient available resources at state level for measuring GHG emissions	Track GHG-reduction progress statewide	Investigate feasibility of merging results of existing modeling efforts, and supplementing to account for areas not currently covered by local models. Once such an approach has been established, repeat this process on an annual basis (or more frequently) to measure trends.
		Apply a bottom-up approach (such as EPA's MOVES run at the county level) for the state as a whole.
Poor and/or inconsistent local data from MPO (and other) TDMs, few resources at state level for measuring GHG emissions	Track GHG-reduction progress statewide	Use statewide fuel sales data to calculate CO_2 (or CI) emissions statewide. If possible, gather results of more resource intensive (i.e. bottom-up) analyses from neighboring states to determine whether a spatial mismatch between fuel sales and consumption may exist. If mismatch exists, determine its magnitude and adjust finding accordingly. Repeat this process on an annual basis (or more frequently) to measure trends.
Poor and/or inconsistent local data from MPO (and other) TDMs, sufficient resources at state level for measuring GHG emissions	Track GHG-reduction progress statewide	Apply a bottom-up approach (such as EPA's MOVES run at the county level) for the state as a whole.

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