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ABSTRACT

Problem, research strategy, and findings: State, local, and private-sector climate policies increasingly require estimates of site-generated vehicle miles traveled (VMT) for individual properties. No standard, agreed-upon method exists for this purpose. If alternative methods produce reasonably consistent results, then an analyst may select a method based on convenience. The purpose of this study was to determine whether this is the case. We reviewed existing applications and methods for estimating site-generated VMT, which can be conceptualized as the product of site-level trip generation and average length of a site-generated trip. We identified four plausible methods for estimating site-level trip generation and three for estimating average lengths of site-generated trips. Combining these yielded 12 methods for estimating site-generated VMT. We applied these methods to estimate trip generation, average trip length, and total VMT generated by eight existing office sites in the San Francisco Bay Area (CA) and the Wasatch Front Region of Utah. We found that trip generation and trip length estimates varied widely, with greater variation in trip generation estimates than in trip length estimates. Variation was magnified when the estimates were multiplied to produce site-generated VMT estimates, with the minimum estimate at a single site ranging from 84% to 96% lower than the corresponding maximum.

Takeaway for practice: In the short term, planning policies requiring site developers or occupants to produce site-level estimates of VMT should specify consistent methods to allow for comparison across sites and over time as needed. In the long term, if VMT is to be used as a performance metric, industry-wide standards for estimating it for both existing and prospective projects are needed. Alternatively, policymakers should consider whether the goals of VMT reduction might be better met with a different performance metric.

Keywords: environmental assessment, greenhouse gas accounting, vehicle miles traveled

Local governments increasingly require vehicle miles traveled (VMT) analysis to evaluate the environmental impacts of developments. In addition, many institutions have voluntarily committed to measuring their own site-generated VMT. National and regional VMT estimates and those for specific roadways have been reported in the United States for decades (Federal Highway Administration, 1954), and researchers have continued to improve estimation methods (Davis, 1997; Federal Highway Administration, 2003; Ha & Oh, 2014; Nasri et al., 2019; Selby & Kockelman, 2013). However, there is no widely accepted method for estimating site-generated VMT. Estimates of site-generated VMT show how much vehicle travel a site causes, rather than where the associated mileage occurs.[1] This calls for a different set of methods than has been applied to segment-level, national, or regional estimation.

Here we describe applications for site-generated VMT estimation and propose a set of criteria that would characterize an ideal estimation method. We summarize the methods used in existing applications and present a plausible set of methods that could estimate site-generated VMT for office buildings and corporate campuses.[2] In our study, we applied these methods to eight sites. We found that trip length and trip generation estimates varied widely by method and that combining these two measures to estimate site-generated VMT magnified the variation present in each. We argue that if VMT is to be used as a performance metric, a standard site-level VMT estimation method should be developed that prioritizes a) consistency, b) cost-effectiveness, c) closeness (i.e., accuracy), and d) conservatism (although we do not suggest that these values should be equally weighted, and we acknowledge that they are in tension with one another). If this is not possible, the goals of VMT reduction would be better served by a performance metric other than estimates of site-generated VMT.

Applications for Site-Level VMT Estimation

New approaches to environmental impact assessment, emerging revenue sources, and corporate greenhouse

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gas (GHG) accounting standards have separately created requirements to estimate site-level VMT generation. In 2013, the California State Legislature passed SB 743, requiring that the transportation impacts of projects subject to state environmental review be evaluated in terms of a metric other than vehicle level of service, which is a measure of traffic congestion and vehicle delay. In 2018, the California Governor's Office of Planning and Research (OPR) selected site-generated VMT to replace level of service. Since then, developers have been required to estimate the contributions of proposed projects to regional VMT. A survey of municipal transportation planners subsequently showed that most viewed VMT as an appropriate metric for locally required traffic impact analyses as well (Volker et al., 2019).

VMT estimates may also inform emerging transportation revenue sources or extensions to existing sources. Some California jurisdictions have considered the adoption of VMT-based transportation impact fees, rather than congestion-based fees, to parallel the use of VMT as an impact metric for environmental assessment (Kwok, 2019).

Transportation utility fees (TUFs) are an emerging VMT-based revenue source for transportation infrastructure (Ewing, 1993; Junge & Levinson, 2012; Voulgaris, 2016). In principle, TUFs allocate revenue collection among properties (rather than among individuals, households, or vehicles) based on each property's use of local roads, which would ostensibly be roughly proportionate to site-generated VMT. Voulgaris (2016) identified 34 municipalities that had implemented TUF ordinances as of 2016.

Corporate accounting of GHG emissions also uses site-generated VMT estimates. The GHG Protocol (World Business Council for Sustainable Development & World Resources Institute, 2004) is the current standard for corporate GHG accounting and reporting. It has defined corporate emissions in three distinct scopes. Scope 3 includes travel to and from the firm's location(s). Scope 3 emissions can represent a nontrivial proportion of a firm's total emissions. Huang et al. (2009) estimated that Scope 3 emissions generally represent 70% to 80% of corporate emissions, depending on industry sector. They found that in the higher education sector, employee commuting represented about a quarter of all emissions.

Given that such a high proportion of GHG emissions in the higher education sector are from employee commuting, it is worth mentioning the Second Nature Climate Commitment pledge (Second Nature, 2016), which more than 300 college and university presidents have signed, committed to reporting two sources of Scope 3 emissions: student/employee commuting and air travel (Dyer & Dyer, 2017; Second Nature, 2018).

Criteria for a VMT Estimation Method

We propose a framework for evaluating site-level VMT estimation methods based on *four Cs*: consistency, cost-effectiveness, closeness, and conservatism. We do not suggest that these values should be equally weighted, and we acknowledge that they are frequently in direct tension with one another.

Consistency

Consistency refers to the potential for analysts to apply a method in the same way across a variety of sites or for the same site over time. For comparisons across sites and over time to be meaningful, estimation methods should be consistent. In addition, because VMT estimates for existing developments ostensibly represent an objective reality, it would be desirable to use the same estimate (and thus the same method) for all purposes. For example, if a corporate campus were to use one VMT generation estimate for purposes of an environmental impact assessment and another to determine its contribution to a municipal TUF, this would damage the credibility of both estimates.

Cost-Effectiveness

Cost-effectiveness refers to the potential for analysts to apply a method at a low cost. Each of the applications described above requires resource-constrained stakeholders to estimate VMT frequently. A method that requires substantial time and resources is unlikely to be adopted for voluntary applications (like the GHG Protocol or the Second Nature Climate Commitment) and would be impractical for mandatory applications that require frequent estimation.

Closeness

Closeness refers to the accuracy of estimates produced by a method. Although closeness (accuracy) is important, it is generally unknowable. Direct measurement of VMT is not feasible for most existing sites (except in cases where the travel of all site visitors can be surveilled both on- and off-site). This limitation also precludes ex post evaluations of the closeness/accuracy of estimates for proposed developments.

Conservatism

Because no estimation method is perfectly accurate, it is desirable for estimates to be *conservative*, in the sense that errors are in a direction that minimizes risk. Whether it would be conservative to overestimate or underestimate site-generated VMT depends on the decisions those estimates will inform. If the goal is to reduce or minimize increases in VMT, a conservative

VMT estimate is an overestimate, which minimizes risks of insufficient action to reduce VMT. However, conservatism with respect to minimizing one type of risk might result in unacceptable levels of risk in other domains. For example, if the goal is to provide adequate affordable housing (Ding & Taylor, 2022), attract development that can create jobs, increase tax revenue, or ensure an efficient distribution of VMT mitigation resources, a conservative estimate might be one with a higher probability of being an underestimate. The use of conservatism as a criterion to evaluate an estimation method requires the evaluator to identify and prioritize the risks they wish to address.

Existing Methods for Site-Level VMT Estimation

Three existing and emerging applications for site-generated VMT estimation are environmental assessment (notably in California), estimation of fees (such as transportation utility fees), and corporate GHG accounting. Estimation methods for site-generated VMT vary across these applications.

Environmental Assessment

Methods for estimating VMT for environmental assessment (as required in California) are generally more sophisticated than VMT estimation methods for other applications (such as allocating TUFs or applying corporate GHG accounting standards). However, there is no widely accepted estimation method for this purpose. The California OPR has simply required that estimates use “comparable data and methods” (Governor’s OPR, 2018, p. 30) and indicated that “[t]ravel demand models, sketch models, spreadsheet models, research, and data can all be used to calculate and estimate VMT” (Governor’s OPR, 2018, p. 30).

Lee et al. (2017) analyzed five frequently used sketch models in California: CalEEMod, California Smart Growth Trip Adjustment Tool, Green Trip Connect, MXD, and Sketch 7. CalEEMod calculates site-level VMT as the product of a trip generation estimate and a trip length estimate. Initial estimates are adjusted based on site characteristics and elasticities published by the California Air Pollution Control Officers Association (Lee, 2010).

The California Smart Growth Trip Adjustment Tool and MXD both estimate trip generation associated with a proposed project and multiply those estimates by trip lengths from the California Statewide Travel Demand model (Lee et al., 2017).

GreenTrip Connect and Sketch 7 estimate VMT directly rather than as a product of estimated trip generation and trip length (Lee et al., 2017). GreenTrip Connect estimates are based on observed relationships between household VMT based on household income, regional context, and location efficiency (Newmark & Haas, 2016). Because GreenTrip Connect is based on household VMT estimates, it can only be used to estimate site-level VMT for residential developments (Lee et al., 2017). Sketch 7 is a spreadsheet model that estimates VMT for a variety of development types based on *seven Ds*: density, diversity, distance, design, destination, demographics, and development scale (Milam & Pack, 2019). It has been applied to the Sacramento region, but versions have been calibrated for other California regions as well (Lee et al., 2017).

Lee et al. (2017) conducted case studies to analyze the performance of each of these methods and found notable differences between the tools and concluded that the accuracy of the absolute VMT estimates from each tool is uncertain.

Fee Estimation

The use of site-generated VMT as a basis for traffic impact fees has been proposed in California as an analog to the use of VMT in environmental assessment (Kwok, 2019), and it would presumably rely on similar estimation methods.

The establishment of the earliest transportation utility fees predates the development of the tools described above and surveyed by Lee at al. (2017), and TUF estimation methods use less sophisticated methods to estimate each property’s contribution to total VMT. In a survey of cities that have implemented TUFs, Voulgaris (2016) found that the most common basis for TUFs is the number of trips generated by each site, based on published rates. This is proportional to a site-generated VMT estimate only if one assumes that all trips within the city have similar trip lengths or if rates are adjusted to account for trip lengths.

As of 2016, the only city with a TUF ordinance that accounted for variation in both trip generation and trip length was Phoenix (OR; Voulgaris, 2016). Trip length factors in Phoenix are established for commercial properties by city council (City of Phoenix, Oregon, 2023).

Corporate Greenhouse Gas Accounting

Methods for estimating VMT for the GHG Protocol are likewise lacking. Despite the importance of employee commuting to overall emissions, the GHG Protocol has not specified a method for estimating commute-generated VMT. Second Nature has described gathering data on student and employee commuting as “often the most intensive part of conducting a GHG inventory”

(Second Nature, 2018, p. 5) and has suggested surveys to be a common method for collecting this data.

Potential Data Types for Estimating Components of Site-Generated VMT

Site-level VMT estimates can be simplified as the product of two values: site-level vehicle trip generation (the number of daily trips that begin and end at the site) and average length of vehicle trips to the site. Table 1 summarizes data types that can be used to estimate values for these components of site-generated VMT.

Data types for estimating both trip generation rates and average trip lengths include household or establishment surveys, administrative data, mobile device data, and travel demand models. The Institute of Transportation Engineers (ITE) has also published rates for estimating trip generation (ITE, 2017a, 2017b). Analysts can use published rates and travel demand models to estimate values for both existing and prospective developments. Surveys, administrative data, and mobile device data can inform estimates for existing developments. To apply these data to estimate VMT for prospective developments, an analyst would need to collect data at a set of comparable existing sites. None of these data types produce direct measurements of site-generated VMT, even for existing sites. All of them require an analyst to make choices and assumptions to produce an estimated VMT value.

We have evaluated estimates drawing on four of the five data types listed in Table 1 (we have not evaluated estimates based on survey data). We discuss each of the data types listed in Table 1 in further detail below.

Published Rates

Published rates have been generated from data collected at existing (at the time of the data collection) sites, and analysts can use them to estimate trip generation at existing or proposed sites. Analysts commonly use ITE rates for estimating trip generation in several planning and engineering contexts, and ITE rates have been incorporated (with adjustments) into three sketch planning tools for estimating site-generated VMT for environmental assessment in California: CalEEMod (ICF et al., 2022), California Smart Growth Trip Adjustment Tool (Handy et al., 2013), and MXD. Although ITE rates are widely used, many scholars have criticized them (Clifton et al., 2013; Currans, 2017; Millard-Ball, 2015; Shoup, 2003, 2018).

Survey Data

National and regional transportation agencies routinely conduct household travel surveys, which can be used to generate trip generation and average trip length estimates for residential land uses. The GreenTrip Connect tool reviewed by Lee et al. (2017) is an example of this use. Household travel surveys are not useful for VMT generation estimates for other land uses. Establishment surveys collect trip generation and trip length data for employee and visitor trips from a commercial site or mixed-use development, but they are costlier and thus rarer than household travel surveys (Muhs, 2013; Selby et al., 2018).

As noted above, Second Nature (2018) has suggested surveys be a common method for estimating site-generated VMT for purposes of corporate GHG inventories. CalEEMod estimates trip lengths by default from the 1999 California Household Travel Demand model but allows users to replace these default values with more recent, local data (ICF et al., 2022; Lee et al., 2017).

Administrative Data

For some land uses, tax records and other administrative data can offer a similar level of detail to a typical

Table 1. Potential data sources for estimating components of site-generated VMT.

Data type	Can produce estimated trip generation	Can produce estimated trip lengths	Can be used for existing developments	Can be used for prospective developments	Evaluated in this study
Published rates	Yes	No	Yes	Yes	Yes
Surveys	Yes	Yes	Yes	Would require the use of existing comparison sites	No
Administrative data	Yes	Yes	Yes	Would require the use of existing comparison sites	Yes
Mobile device data	Yes	Yes	Yes	Would require the use of existing comparison sites	Yes
Travel demand models	Yes	Yes	Yes	Yes	Yes

establishment survey. For example, if employee commuting represents almost all the VMT generated by a site, and there are minimal opportunities to commute by non-auto modes, the number of employees can offer an approximation of the number of trips generated by the site, and the distances of employee addresses from the site can be used to approximate trip lengths. These are strong assumptions, but they may be relevant at suburban office parks.

Mobile Device Data

A few vendors, including AirSage and StreetLight Data, have aggregated data collected from location-based smartphone applications to provide information on regional travel patterns to transportation planners and researchers. StreetLight Data has specifically marketed its products for use in VMT analysis to meet environmental assessment requirements in California (StreetLight Data, 2021). Available data typically have included the weighted number of devices observed traveling to defined areas (such as individual sites) as well as the distance those devices traveled to reach those areas. Weights have been assigned using proprietary algorithms to account for the fact that some travelers may not carry a smartphone and others may travel with multiple devices. In expanding and aggregating the location-based smartphone data, vendors have attempted to classify trips by mode. These methods have improved with time but have not always been reliable (Burkhard et al., 2020).

Travel Demand Models

Planning agencies commonly maintain regional travel demand models, which have been shown to generate reasonable estimates of regional VMT (within 10%; Rodier, 2004). Such models provide detailed estimates of site-level trip generation and trip lengths, although estimate accuracy degrades at high level of disaggregation, making them less useful for site-level estimates than for regional estimates. Two tools used for estimating site-generated VMT for environmental impact assessment in California, the California Smart Growth Trip Adjustment Tool and MXD, have used average trip lengths from the California Statewide Travel Demand model (Lee et al., 2017).

Combined Methods

All five data types described above can be used to estimate a site's trip generation, and four of the five (all except published ITE rates) can be used to estimate the average length of trip a site generates. The four data types for estimating site-generated trip lengths and the five data types for estimating the number of site-generated trips could theoretically combine to generate 20 methods for estimating VMT generation. We have evaluated 12 of those in this study. Table 2 summarizes all 20 potential methods.

Corporate GHG accounting has commonly relied on surveys alone (as suggested by Second Nature, 2018, for example). TUF rate assessment has commonly used ITE trip generation rates alone (essentially assuming constant trip lengths; Voulgaris, 2016). Environmental assessment and VMT-based impact fees in the California context may use mobile device data alone or use sketch planning tools such as those reviewed by Lee et al. (2017). Two of these (California Smart Growth Trip Adjustment Tool and MXD) have combined trip generation data from published rates with trip length data from travel demand models, and one (CalEEMod) has combined trip generation data from published rates with trip lengths from surveys (Lee et al., 2017).

Study Methodology

In this study, we have compared site-level daily VMT estimates for eight study sites in two regions (the San Francisco Bay Area of California and the Wasatch Front region of Utah). We used four of the five data types listed in Table 1: published rates, administrative data, mobile device data, and travel demand models.

Published Rates

We calculated daily trip generation for each site using rates from the 10th edition of ITE's *Trip Generation* (ITE, 2017a), which includes trip generation rates for a variety of land use types and urban contexts. For the office sites evaluated in this study, we used rates for Land Use Code 710 (General Office Building) for the General Urban/Suburban context, resulting in an average rate of 9.74 daily trips per 1,000 ft^2 of office space or 3.28 daily trips per employee. We sourced building square footage from CoStar in 2020.

Administrative Data

For each census block in the United States, the LEHD Origin–Destination Employment Statistics (LODES) product includes the number of employees who work in that census block and live in each of the other census blocks in the nation. These data have resulted from a collaboration between various federal statistical agencies and were constructed from individual tax records containing the home address and work billing address of most workers in the United States. Details on these data—including the discussion of imputation methods that the Census Bureau uses to complete the data—have been given by Graham et al. (2014). LODES data

Table 2. Potential methods for estimating site-generated VMT.

VMT estimation method	Trip generation data type	Trip length data type	Similar application in practice	Evaluated in this study
Rate-Survey	Published rates	Surveys	CalEEMod	No
Rate-Admin	Published rates	Administrative data		Yes
Rate-Device	Published rates	Mobile device data		Yes
Rate-Model	Published rates	Travel demand models	California Smart Growth Trip Adjustment Tool and MXD	Yes
Rate-Assumed	Published rates	None	Most TUF ordinances	No
Survey-Survey	Surveys	Surveys	Corporate GHG accounting, GreenTrip Connect	No
Survey-Admin	Surveys	Administrative data		No
Survey-Device	Surveys	Mobile device data		No
Survey-Model	Surveys	Travel demand models		No
Admin-Survey	Administrative data	Surveys		No
Admin-Admin	Administrative data	Administrative data		Yes
Admin-Device	Administrative data	Mobile device data		Yes
Admin-Model	Administrative data	Travel demand models		Yes
Device-Survey	Mobile device data	Surveys		No
Device-Admin	Mobile device data	Administrative data		Yes
Device-Device	Mobile device data	Mobile device data	Products marketed by mobile device data vendors	Yes
Device-Model	Mobile device data	Travel demand models		Yes
Model-Survey	Travel demand models	Surveys		No
Model-Admin	Travel demand models	Administrative data		Yes
Model-Device	Travel demand models	Mobile device data		Yes
Model-Model	Travel demand models	Travel demand models		Yes

can offer a reasonable approximation for the number of people commuting to a site each day as well as the distance of their commutes.

To calculate site-level trip generation from the LODES data, we first obtained the number of workers at the site[3] and multiplied by 2, assuming that workers arrive and depart once each during the day. We then scaled this estimate to vehicle trips by applying the vehicle mode share from the American Community Survey at the home block group level. We applied vehicle occupancy factors for the proportion of trips that American Community Survey reports as carpool trips. We calculated the distance from each work block centroid to each home block group centroid using the OSMnx package for Python (Boeing, 2017). We adjusted mode shares to remove unreasonable mode choices[4] and converted to vehicle trips. This approach resulted in an estimate that more than 98% of all employees at each site commuted by driving alone.

Mobile Device Data

We used vehicle trip generation estimates and associated average trip lengths from mobile device data that StreetLight Data Inc. had aggregated and donated for this research.

Travel Demand Models

Both regions from which our study sites were drawn had available travel demand models based on the ActivitySim modeling framework. The Association of Metropolitan Planning Organizations has developed ActivitySim, an open-source activity-based modeling framework. The current ActivitySim framework replicated the Metropolitan Transportation Council (San Francisco Bay Metropolitan Planning Organization Travel Model One activity-based model; Erhardt et al., 2012). Other regions have applied ActivitySim as a test model or for research projects, including in the Wasatch Front

Regional Council (Salt Lake City MPO) modeling area. The San Francisco Bay version of ActivitySim has been calibrated to match 2010 conditions; the Salt Lake City ActivitySim implementation used the San Francisco Bay choice coefficients, calibrated to replicate 2018 Wasatch Front Regional Council mode share statistics.

Activity-based models like ActivitySim contain a complete record of the daily trip chains of a synthetic population. To examine the VMT impacts of a particular site, we first ran the ActivitySim scenarios as calibrated with the original socioeconomic data file. We then ran an alternate scenario for each collection of sites, removing the site employment, determined from LEHD data. The number of vehicle trips that no longer traveled to the site in the alternate scenario was used as the estimated trip generation, and the average length of these trips was also recorded.[5] This method yielded a single average trip length for each entire traffic analysis zone, because the model could not reveal which site in the zone people travel to.

Site-Level VMT Estimates

Using the data types described above, we estimated site-generated VMT using 12 of the 20 methods listed in Table 2. For these 12 methods, Table 3 further illustrates the relationships between the data types listed in Table 1 and the methods listed in Table 2. Three methods relied on a single data type, and the remaining nine were hybrid methods that combined multiple data types. This resulted in 12 unique estimates of site-generated VMT for each of the study sites. Some of the hybrid methods would be unlikely in practice, but we included them for completeness. We compared these 12 estimates to determine whether these methods converged on a range of likely values.

Study Sites

We estimated site-generated VMT for each of eight sites: four in the San Francisco Bay Area and four in the Wasatch Front Region. The availability of an ActivitySim implementation for both regions allowed the travel demand model estimates to be derived from the same model framework, though an ActivitySim model (or any model based on any framework) could be developed for any region, given adequate time and resources.

Figure 1 shows the locations of the Utah study sites and Figure 2 shows the locations of the California study sites.

All sites comprised a single land use (general office space without substantial retail or residential components), and each represented one or more entire census blocks. This made commuting estimates based on LEHD data a reasonable approximation of total travel for these sites.

Comparisons Across Sites

To describe variation in estimates across sites, we calculated symmetrical percentage difference from the average, calculated as shown in Equation 1:

$$SPDA = \frac{2(e-a)}{(e+a)}, \tag{1}$$

where *SPDA* is the symmetrical percentage difference from the average; *e* is the estimated value for a particular site, by a particular method; and *a* is the average value for a particular site, across all methods.

Higher-magnitude values suggest greater variation among estimates by different methods for the same site. The maximum theoretical value for symmetrical percentage error is asymptotic to 200% (which would be observed for a non-zero estimate at a site as the average estimate approaches zero) and the minimum theoretical value is –200% (which would be observed for an estimate of zero if the average estimate across all methods was not zero).

Comparison of Alternative Site-Level VMT Estimates

The purpose of this study was to determine how much estimates vary among alternative methods. We found substantial variation in trip generation, trip length, and VMT estimates.

Trip Generation Estimates

Figure 3 and Table 4 summarize the variation in trip generation estimates. The Technical Appendix shows the complete results.

For each California site, the highest estimate ranged from 3.8 to 12 times the lowest. Published rates

Table 3. Summary of methods for estimating site-generated VMT.

	Trip generation data types			
Trip length data types	Mobile device data	Administrative data	Travel demand models	Published rates
Mobile device data	Device-Device	Admin-Device	Model-Device	Rate-Device
Administrative data	Device-Admin	Admin-Admin	Model-Admin	Rate-Admin
Travel demand models	Device-Model	Admin-Model	Model-Model	Rate-Model

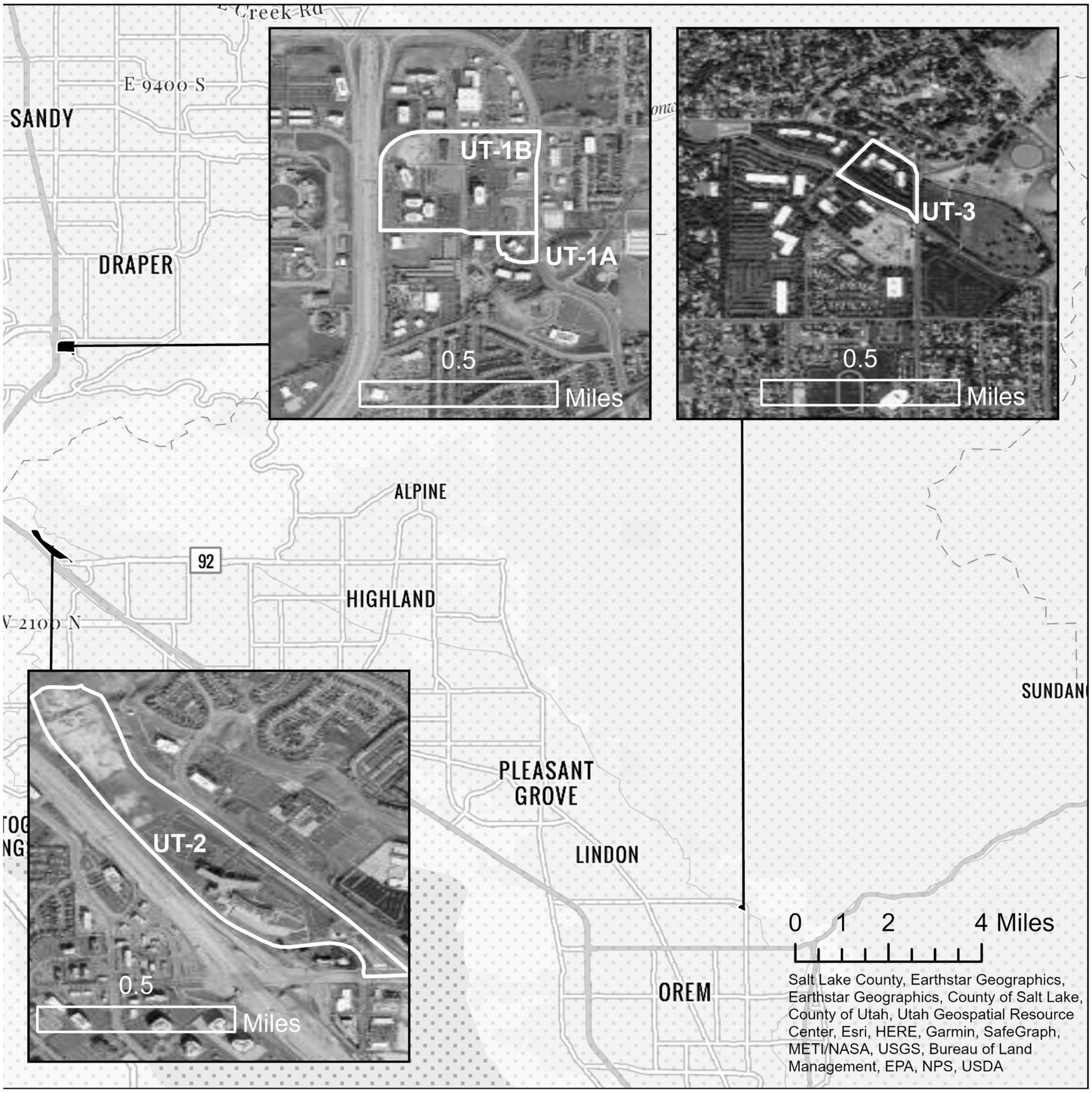

Figure 1. Locations of Utah study sites.

consistently yielded the highest estimate for California sites. The next highest estimate for each site was 1.3 to 2.4 times the lowest estimate.

Although published rates consistently yielded the highest estimates at the California sites, they consistently yielded the lowest estimates at the Utah sites.[6] The ranks of the estimates from administrative data also varied between the two regions. Estimates based on administrative data were consistently highest or second highest among the Utah sites and lowest or second lowest among the California sites.

Other than estimates from published rates, estimates from mobile device data were highest for seven study sites and estimates from travel demand models were the lowest for six study sites.

Trip Length Estimates

Figure 4 and Table 5 summarize the variation in average trip length estimates for each site. The Technical Appendix shows the complete results.

For each California site, the highest estimate ranged from 2.1 to 2.4 times the lowest. The variation among the Utah sites was greater than that of the California sites, with the highest estimates ranging from 2.3 to 3.1 times the lowest. Ranking the estimates from highest to lowest yielded a consistent ranking across most sites,

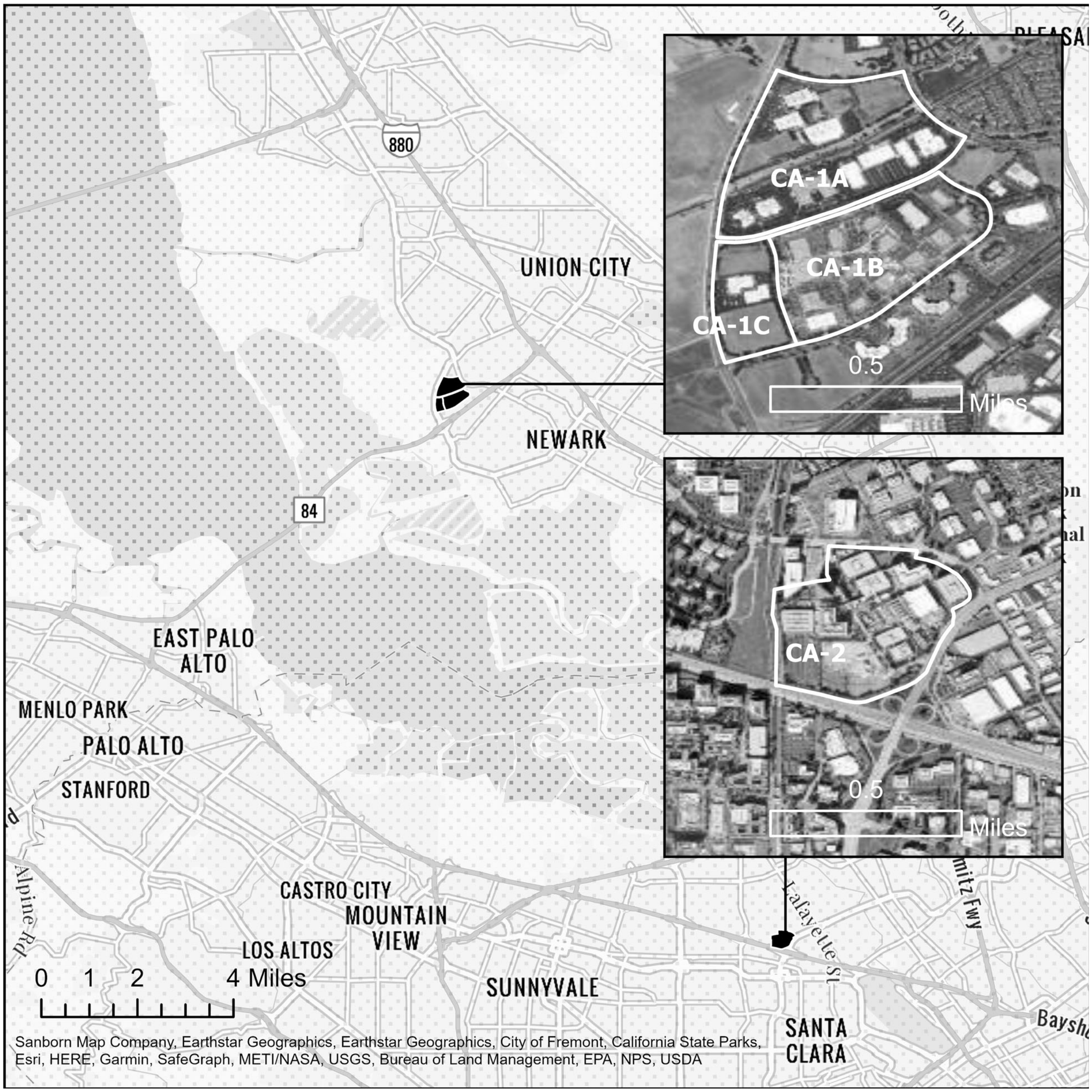

Figure 2. Locations of Bay Area study sites.

with administrative data yielding the highest estimates for all sites and travel demand models yielding the lowest estimates for seven sites.

VMT Estimates

Figure 5 and Table 6 summarize VMT estimation results. The Technical Appendix shows the full results. Multiplying trip generation by trip lengths compounds the variation in both. The highest estimate for California sites ranged from 10 to 27 times the lowest. The highest estimate for Utah sites ranged from 6 to 10 times the lowest.

Multiplying the highest trip generation estimate by the longest trip length estimate yielded the highest VMT estimate. For California sites, this was the combination of trip generation estimates from published rates and trip length estimates from administrative data (Rate-Admin). For three Utah sites, the highest VMT estimates came from combining the trip generation estimate from mobile device data and trip length estimates from administrative data (Device-Admin).

Likewise, multiplying the lowest trip generation estimate by the shortest average trip length yielded the lowest VMT estimate. For all Utah sites, this was the combination of trip generation estimates from

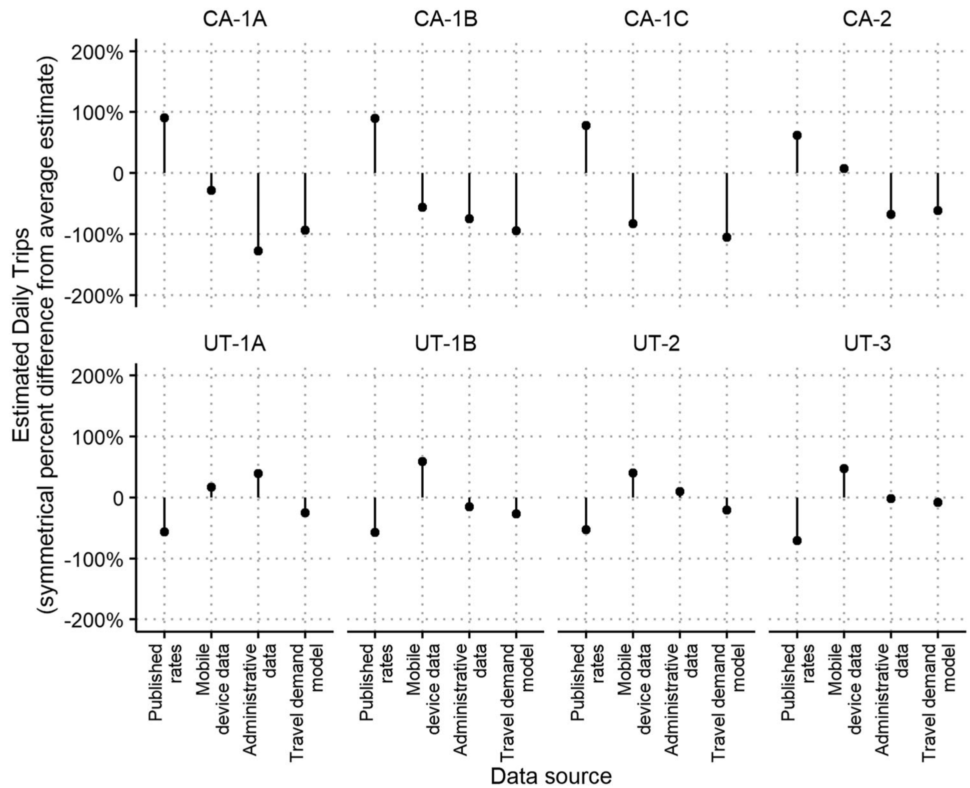

Figure 3. Variation in daily trip generation by estimation data type.

Table 4. Summary of daily trip generation estimates.

		Minimum estimate		Maximum estimate	
Site	**Average estimate**	**Value**	**Data type**	**Value**	**Data type**
CA-1A	4,466	987	Administrative data	11,902	Published rates
CA-1B	3,337	1,189	Travel demand model	8,774	Published rates
CA-1C	789	244	Travel demand model	1,797	Published rates
CA-2	12,589	6,234	Administrative data	23,876	Published rates
UT-1A	556	312	Published rates	826	Administrative data
UT-1B	2,608	1,439	Published rates	4,775	Mobile device data
UT-2	2,703	1,578	Published rates	4,057	Mobile device data
UT-3	447	214	Published rates	725	Mobile device data

published rates and the trip length estimates from the travel demand model (Rate-Model). The Rate-Model method yielded the third-highest estimate for all California sites. For two California sites, the lowest VMT estimates came from using the travel demand model for both trip generation and trip length (Model-Model).

Evaluation of Estimates

As we discussed at the outset, environmental assessment for prospective developments, fee assessment for existing and prospective developments, and GHG accounting for existing developments have increasingly required VMT estimates at the site level. If these applications are to continue to use site-generated VMT as a performance or evaluation metric, it would be desirable for analysts to have a method for estimating VMT that is consistent, cost-effective, accurate (or close), and conservative (to the extent that it is not accurate). Given the findings presented here, how do the methods we evaluated perform along these four dimensions?

Consistency

Of the trip generation data types we describe, the use of published rates lends itself best to consistency. The

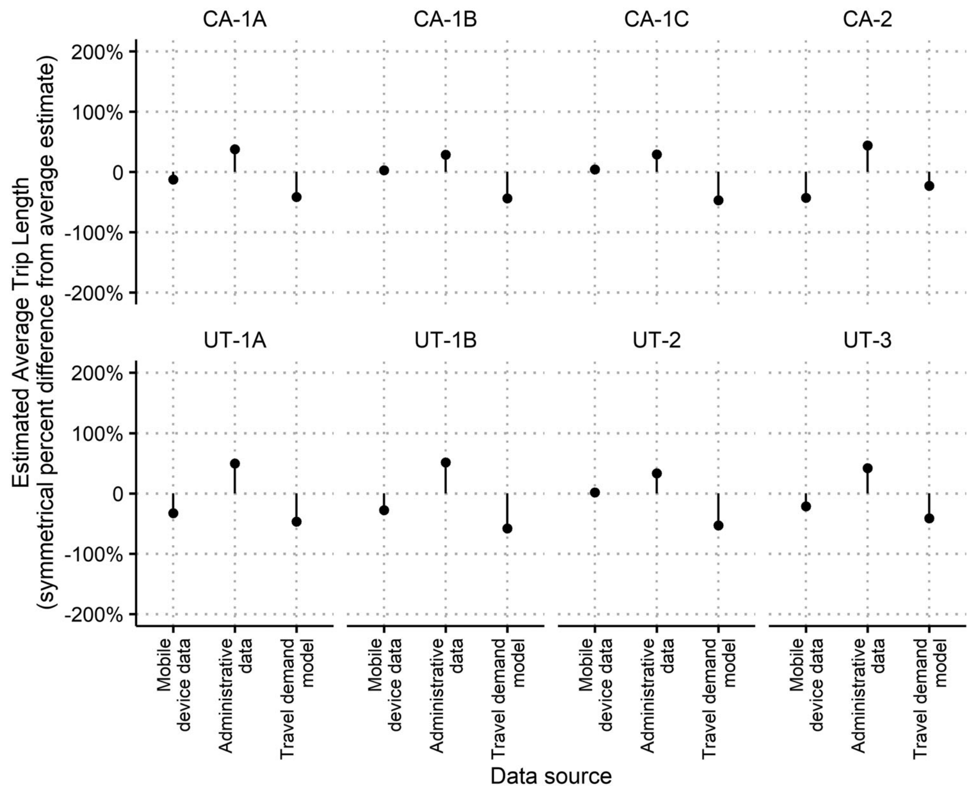

Figure 4. Variation in average trip length by estimation data type.

Table 5. Summary of daily trip length estimates.

		Minimum estimate		Maximum estimate	
Site	**Average estimate (miles)**	**Value (miles)**	**Data type**	**Value (miles)**	**Data type**
CA-1A	24.9	16.3	Travel demand model	36.5	Administrative data
CA-1B	25.5	16.3	Travel demand model	34.0	Administrative data
CA-1C	26.4	16.3	Travel demand model	35.3	Administrative data
CA-2	24.8	16.0	Mobile device data	38.7	Administrative data
UT-1A	20.3	12.6	Travel demand model	33.6	Administrative data
UT-1B	22.9	12.6	Travel demand model	38.8	Administrative data
UT-2	19.7	11.4	Travel demand model	27.6	Administrative data
UT-3	22.6	14.9	Travel demand model	34.7	Administrative data

need for a consistent trip generation methodology might explain the persistence of ITE rates despite scholarship criticizing their use, especially in urban areas (Clifton et al., 2013; Currans, 2017; Millard-Ball, 2015; Shoup, 2018).

None of the trip length estimation methods we describe here lends itself to consistent application across land uses and regions. Travel demand models can provide estimated trip lengths within a given region but may vary widely across regions in terms of methods and assumptions. The use of administrative data is useful for sites where employee commutes are the primary source of VMT but less useful for sites that generate a wider variety of trip purposes, such as retail and residential sites. Although mobile device data approximate a direct measurement of site-generated VMT, the proprietary algorithms that generate origin–destination matrices from location data presumably vary from one data vendor to another, and a data vendor may modify its algorithms over time.

Mobile device data and administrative data can be used to measure current (or recent) VMT. They cannot estimate VMT for proposed land use changes, as would be required for environmental impact assessments.

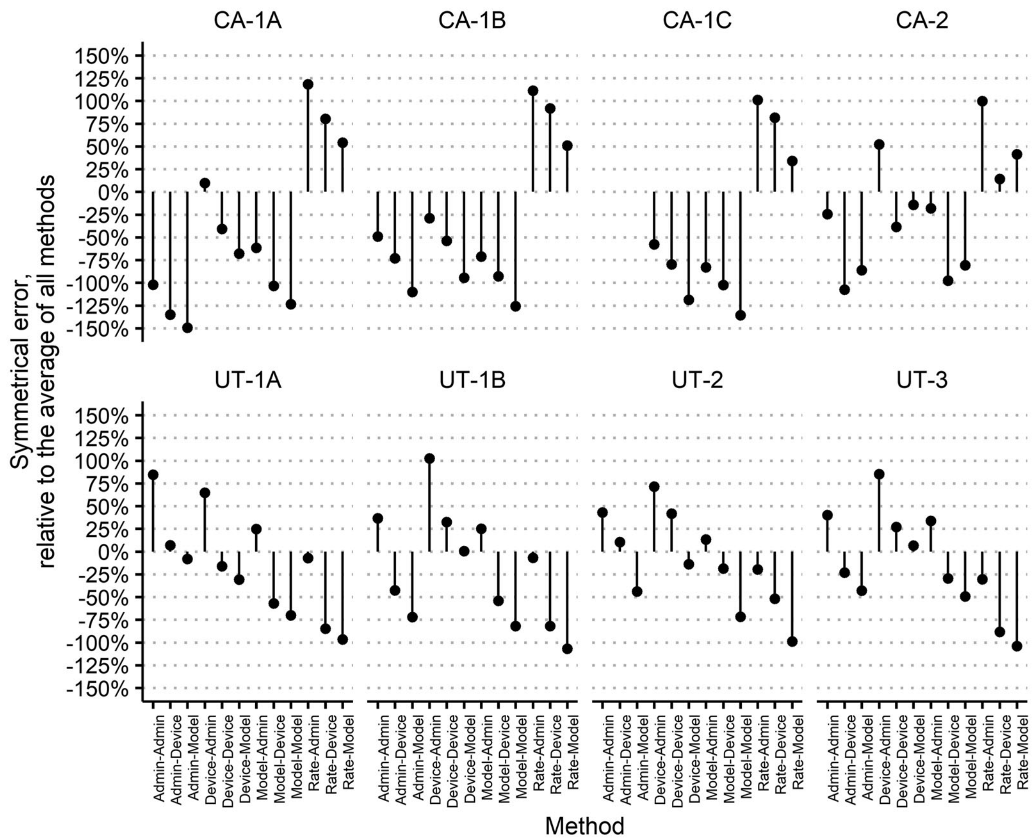

Figure 5. Variation in site-generated VMT by estimation method.

Table 6. Summary of daily VMT estimates.

		Minimum estimate		Maximum estimate	
Site	**Average estimate**	**Value**	**Method**	**Value**	**Method**
CA-1A	111,211	16,088	Model-Admin	434,423	Rate-Admin
CA-1B	85,033	19,384	Admin-Admin	298,316	Rate-Admin
CA-1C	20,782	3,970	Model-Admin	63,344	Rate-Admin
CA-2	308,721	92,802	Admin-Admin	924,001	Rate-Admin
UT-1A	11,276	3,931	Admin-Model	27,754	Admin-Model
UT-1B	59,779	18,131	Admin-Admin	185,270	Device-Admin
UT-2	53,071	17,989	Admin-Admin	111,973	Device-Admin
UT-3	10,111	3,189	Model-admin	25,158	Device-Admin

However, they could estimate VMT at comparable sites, and those estimates could inform predictions for prospective sites.

Cost

The data collection involved in generating the trip generation rates published by ITE required substantial resources, much of which came in the form of volunteered time and donated data from projects spanning decades. Now that those data are published, the cost of applying those rates to estimate trip generation for an existing or proposed development is relatively low. The low cost of using ITE rates likely explains their widespread use. Administrative data that are publicly and freely available, such as the data we used from LEHD, are likewise low cost. Establishment surveys that would be useful for generating VMT estimates are quite costly and rarely done, which is why we did not include them in this study. Mobile device data can be expensive to obtain outside of regular contracts. In regions that maintain regional travel demand models, the agencies that maintain them typically make them available without cost. However, not all regions maintain an appropriate travel demand model, and developing one for a specific project would be costly. Moreover, the specialized training and time required to specify and analyze model scenarios might make their applicability to this problem expensive in staff or analysis time.

Closeness

We use the term *closeness* to refer to the accuracy of a particular method. It is impossible to evaluate the accuracy of any method presented here because actual site-generated VMT cannot be directly measured. Research on forecast accuracy has suggested that averages of estimates produced by several methods are more accurate than any single method (Makridakis et al., 1982, 1993; Makridakis & Hibon, 2000). If this is true of the estimates produced for this study, then the most accurate method would be the one that produced values closest to the average across all methods, which we can express as symmetrical percentage difference (see Equation 1), as Figure 6 illustrates. Empty circles represent average error across all sites. Methods for which this circle is near zero are those that produce estimates that are, on average, closest to the average across all methods. This suggests greater accuracy, to the extent that Madridakis et al.'s (1982, 1993; Makridakis & Hibon, 2000) findings (that averages across methods are more accurate than any individual method) can be generalized to the methods in this study.

If the average across all methods approximates the actual value, two methods—Rate-Device and Admin-Admin—have the best average accuracy. However, these two methods have the widest range of accuracy, so the accuracy of the estimate these methods yield for any site is much worse.

Conservatism

Although closeness (accuracy) should take precedence over conservatism, we acknowledge that perfect accuracy is not possible and recommend that there be a preference toward methods with estimates that are biased in the direction that minimizes risk. Is it better to overestimate or underestimate site-generated VMT? Carbon reduction goals might be best met by overestimating site-generated VMT and thereby increasing the likelihood that steps will be taken to reduce it. However, there are also risks associated with overestimation, especially when a method overestimates VMT by as much as 500% or 600%, as some of the methods presented here might. TUFs based on overestimated VMT for commercial properties might have the effect of unnecessarily limiting local economic growth.[7] Because revenues from development impact fees must be spent on mitigation, overestimation of VMT in this context could direct investments in transit, bike, and pedestrian infrastructure toward places with more new development and away from areas where those investments could have a greater impact. Environmental impact assessment methods that dramatically overestimate site-generated VMT could limit economic growth as well as the supply of housing and other necessary land uses. A corporation that, through its application of the GHG Protocol, estimates that employee commuting represents a large-share percentage of its total emissions when the actual contribution is quite minor might allocate resources to reducing employee commuting when those resources would have been more effective in improving the energy efficiency of its buildings. Ultimately, conservatism is an important consideration given that perfect accuracy is unattainable, but it should not be used to excuse wildly inaccurate or uncertain estimates.

Again, when we took the average across all methods as an approximation to an actual value (as illustrated in Figure 5), we found that seven of the 12 methods consistently overestimated VMT for Bay Area sites and underestimated VMT for Utah sites. Three methods consistently underestimated VMT for Bay Area sites and overestimated VMT for Utah sites. These regional differences raise concerns about applying methods that have been developed in one region (California, for example) to other regions (e.g., other regions that are considering adopting California's VMT-based approach to environmental assessment).

In the specific case of environmental assessment in California, whether an estimate is conservative may depend on whether the estimate is above or below the threshold that would trigger the need for mitigation, which the state has defined as 15% below the regional average for a given land use (Governor's OPR, 2018). If all methods would yield VMT estimates below that threshold, the choice of method would not influence the need for mitigation. In the San Francisco Bay Area of California, this value as of writing was 17.3 miles per employee, based on the current Metropolitan Transportation Council travel demand model. For each of the three California sites for which employee counts were available from LEHD, the minimum VMT estimate across all methods ranged from 21.3 miles to 27.8 miles, so the choice of method in these instances would have important implications for the amount and type of mitigation that would be required if these sites were being proposed as new developments. The Technical Appendix includes the estimated VMT per employee by each method for each of these three sites.

Conclusion

Although the findings for these particular methods and these particular sites are unlikely to be generalizable,

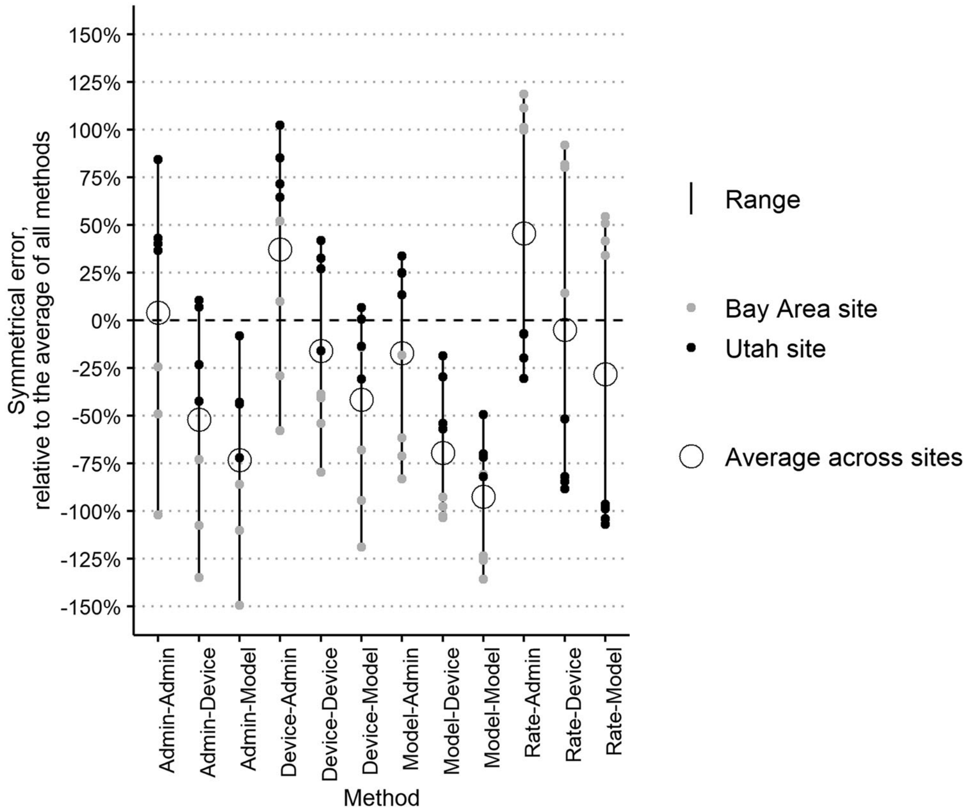

Figure 6. Error of VMT estimates relative to the average across methods.

this study highlights the low reliability of estimates across reasonable methods and large influence that the selection of a method can have on estimates of site-generated VMT.

In the short term, we recommend that planning policies requiring the estimation of site-generated VMT explicitly specify methods to produce these estimates. In the long term, if VMT is to be used as a performance metric or as a project evaluation measure, we recommend the development of an industry-wide standard that achieves acceptable levels of consistency, cost-effectiveness, closeness, and conservatism.

The most common method for estimating site-level trip generation (using published ITE rates) is deeply flawed. It has become entrenched due to:

1. the low cost of finding and applying a relevant rate (although the data collection required to develop these rates is quite costly);
2. the consistency with which rates can be applied across a variety of land uses and contexts (although this consistency often means they are applied in contexts in which they may be inappropriate); and
3. their conservatism in the direction of ensuring adequate roadway space for anticipated traffic (which may not be an appropriate planning goal).

Combs et al. (2023; Combs & McDonald, 2021) have offered more detailed discussions of the barriers to changing entrenched practices in estimating trip generation and in traffic impact assessment more broadly. As the need for site-level VMT estimates is emerging for multiple policy applications, it is critical that the transportation planning and engineering professions avoid the entrenchment of standard methodologies that replicate the mistakes of the past.

One way to meet this challenge would be for an industry organization to develop a database or set of methods like ITE's (2017a, 2017b) *Trip Generation* manual that could be used to estimate average trip lengths. Methods might necessarily differ by land use. The focus of our study has been on office land uses, which present greater challenges in VMT estimation than residential uses do but fewer challenges than retail and service land uses do. Retail and service land uses serve visitors about whom much less information is available than about residents of a residential development or employees at an office or industrial site. The development of a resource that would address the need for consistency, cost-effectiveness, closeness, and conservatism for one or more land use categories would be an important avenue for future research. The results of such research should be incorporated in the education and training of transportation professionals.

It might be impossible for a single method to meet the criteria of consistency, cost-effectiveness, closeness, and conservatism. Consistency in method might only be possible within categories of land uses or within specific urban form and built environment classifications. Social, cultural, and technological changes might require standard methods to be re-evaluated and revised at regular intervals.

Even with that nuance, perhaps no standard (set of) method(s) can achieve acceptable levels of consistency, cost-effectiveness, closeness, and conservatism. In this case, the goals of VMT reduction might be best achieved through metrics other than site-generated VMT. Metrics describing neighborhood density might signal the potential for shorter trips. Metrics describing transit availability might signal the potential for lower shares of car trips. As an example of incorporating such alternative metrics into environmental assessment, the Governor's OPR in California has suggested that site-generated VMT analysis for purposes of environmental impact assessment is not necessary for affordable housing developments or for sites near transit stations, because these can be assumed to generate relatively low VMT (Governor's OPR, 2018).

Effects of these sorts of proxy metrics on estimates of regional VMT might inform their use to inform the evaluation of existing developments of the selection of sites for new developments. Effects of such metrics on the factors that contribute to VMT, including trip generation and distance of vehicular trips but also mode shares and vehicle occupancy, would be even more useful since they could serve to identify the types of interventions that would be most effective in reducing VMT.

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SUPPLEMENTAL MATERIAL

Supplemental data for this article can be found at https://doi.org/10.1080/01944363.2023.2298962.

NOTES

1. Regulations in California also require the estimation of project-generated VMT for projects that expand roadway capacity. Such estimates are not the focus of this study.

2. Some, but not all, of the methods we applied in this study could be applied to other land uses as well.

3. LEHD data indicated that there were zero employees at one of the Utah sites (UT-1C). For this site, we did not produce a trip generation estimate using administrative data, and we estimated the average trip length by averaging the LEHD-based trip length estimates from adjacent sites.

4. Unreasonableness thresholds were 3 km for walking, 10 km for cycling, and 500 m to access transit. Five of the eight sites had no transit service within 1 km, so we assigned no transit trips to those sites.

5. This estimate includes the vehicle portion of drive-access transit trips and is discounted for vehicle occupancy.

6. This difference seems to come from a substantial difference in employee densities (the number of employees per square foot of gross floor area) between the two regions. This divergence in employee densities may reflect an actual difference in how office space is used in these two regions, or it could be an artifact of how LEHD data are collected.

7. TUF ordinances typically require that fees raise no more total revenue than is required for road maintenance. Overestimating VMT for commercial properties would not increase total revenue but would increase the share of the relative share of revenue collected from commercial properties.

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