Measuring Fundamental Improvements in Sustainable Urban Mobility: The Mobility-Energy Productivity Metric

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Measuring Fundamental Improvements in Sustainable Urban Mobility: The Mobility-Energy Productivity Metric

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ABSTRACT

Recent technological advancements in mobility are creating many options for connecting citizens with employment, goods, and services, particularly in urban areas where modes such as bike and car shares, electric scooters, ridesourcing, and ridesharing are proliferating at a rapid pace. Analysis and tools for overall transportation planning are dominated by urban regional travel demand models whose roots in highway operations poorly reflect the system dynamics in denser areas where parking costs, convenience, and availability—not to mention sustainability concerns and quality of life—are driving people to an ever-greater spectrum of mobility services. In this paper, we present a new paradigm for evaluating mobility options within an urban area. First developed for the U.S. Department of Energy's Energy Efficient Mobility System research program, this metric is termed the Mobility-Energy Productivity (MEP) metric. At its heart, the MEP metric measures accessibility and appropriately weights it with travel time, cost, and energy of modes that provide access to opportunities in any given location. The proposed metric is versatile in that it can be computed from readily available data sources or derived from outputs of regional travel demand models. End times associated with parking, curb access, cost, and reliability and frequency of service need to be carefully considered to obtain an appropriate and accurate perspective when computing the metric. Ultimately, the MEP metric can be used to reflect the impacts of new mobility technologies (transportation network companies, electric scooters), business models (car shares and bike shares), and land-use practices (such as transit-oriented development) on sustainable urban mobility. This paper lays out the need, requirements, and framework for this new metric, and offers it, in collaboration with the American Society for Civil Engineers (ASCE), as a foundational metric for Smart City assessment.

INTRODUCTION

For nearly a century, the automobile has been the primary mode of personal transportation in American life. This remains true today as millions of people rely heavily on cars to connect suburbs with cities or to travel long distances—often out of routine or convenience (Fuller 2018). However, advances in technology are fueling an era of transportation transformation, with the potential to transform a system that has remained virtually unchanged for decades. The challenges of interconnecting our cities and creating a cross-continental transportation system for military purposes spawned the interstate highway system, generating the age of the automobile. In this century, congestion and mobility challenges of rising urban populations are spawning ever-evolving mobility and communications technologies to connect people to goods, services, and employment within a metropolitan and national context—all of which define a high quality of life. Aspiring smart cities are wrestling with questions such as: How does mobility impact a person's quality of life? Would people make different travel choices if they were presented with better information about their mobility options? Would businesses make different location decisions if they could assess the quality of mobility in that area?

The ability to quantify the quality of mobility at a given location is the first step toward answering these questions. In response, an interdisciplinary team at the National Renewable Energy Laboratory (NREL) has developed the Mobility-Energy Productivity (MEP) metric. The MEP metric provides an avenue to not only measure the quality of mobility at a specific location in its current configuration, but also to test how various technological advances (e.g., connected and automated vehicles, plug-in electric vehicles, shared mobility) and infrastructure investments (e.g., building an additional highway lane, constructing a new shopping mall, implementing a transit-oriented development) impact the mobility of that location over time. A location with the highest-quality mobility offers multiple efficient transportation options to a diverse number of opportunities while minimizing time, cost, and energy consumption.

Transportation energy consumption is highly correlated to petroleum use, pollutant emissions, and greenhouse gas production. Versions of the MEP metric can be targeted specifically at these outputs, but the framework herein is generalized to energy. Development of the MEP metric is significant to the U.S. Department of Energy's (DOE's) Systems and Modeling for Accelerated Research in Transportation (SMART) Mobility Consortium, which is developing insights, tools, and technology related to the evolving connected mobility system—informing decision makers about how emerging mobility choices impact quality of life and energy consumption. The MEP metric is also critical to urban transportation planning activities in which current metrics—which are heavily based on infrastructure utilization, overall emissions, carbon dioxide (CO_2), or other outputs—fail to capture fundamental mobility benefits with respect to either time, cost, or energy. The formulation of the MEP metric is based on fundamental requirements that include the following:

- At its heart, the MEP metric is founded on principles of accessibility theory that measure access to a wide variety of goods, services, employment and other activity opportunities.
- The MEP is capable of reflecting the congestion impacts of existing and future modes. To achieve this, the MEP metric is fundamentally based on travel times (and their associated reliability) and cost. As a result, any mode that is adequately modeled for travel time and cost (and its associated energy) as well as any data source or model that outputs travel time within an urban area can serve as input to the calculation of MEP .
- The metric reflects the impact of opportunity distribution (goods, services, employment and other activities). As a result, the metric can provide a barometer to assess planning, transit-oriented development, and other land-use practices that enhance accessibility.

- The measure can be aggregated and disaggregated in space as well as by mode and trip purpose, and it can be weighted with respect to various population subgroups. The metric can be defined for each individual mode, as well as any given combination of modes, for each trip purpose or combination of trip purposes. This property allows the metric to provide a single score for an entire city or to reflect impacts in a specific area, for specific purposes, modes, or population groups. This property is critical in that it allows for the creation of highly informative and intuitive mappings of the MEP metric.
- Lastly, the most important requirement for the MEP metric is that it be practical to implement, whether through existing data or through modeled output from transportation demand models.

The MEP metric presented in this article meets these requirements and is presented as a tool for assessing sustainable urban mobility. To guide the development of the MEP metric, the development team, in close association with the DOE's Energy Efficient Mobility System program management, developed a set of "litmus tests" for the application of the MEP metric. Although not exhaustive, these litmus tests provide a series of thought experiments to ensure that the metric is responsive to envisioned scenarios. A few of these scenarios are listed below, presented in a "What if…" framework.

- If the cost of ride-hailing decreases, allowing more people to access on-demand mobility (assuming increased ride-hailing service does not create additional congestion), then the MEP metric should increase.
- If mobility technologies induce even further commuting distances, encouraging people to live further from their place of employment (everything else being equal), then the MEP metric should decrease.
- If additional bike and pedestrian activities are present in our urban areas, then the MEP metric should increase.
- If vehicle automation makes in-vehicle time more productive (and everything else remains unchanged), then the MEP metric should increase.
- If vehicle and fueling technology improvements increase the aggregate effective miles-per-gallon (MPG) of the fleet, then the MEP metric should increase.
- If ride-sharing increases, then the MEP metric should increase.
- If a trip-maker can reach more grocery stores, restaurants, and job opportunities within the same time, cost, and energy budget, then the MEP metric should increase.
- If automated vehicles provide the mobility-impaired with improved service, then the MEP metric should increase.
- If there are two or more distinct modes providing access to goods, services, and jobs, then the total combined MEP metric should be greater than the MEP metric for any of the modes taken individually.

These are just a few of the thought experiments or litmus tests that the MEP metric was subjected to through its development. The MEP metric has been exercised for a variety of modes and scenarios to test its ability to satisfy these requirements, and a software package is being prepared to interface with regional travel models to test future mobility scenarios.

MEP METRIC METHODOLOGY

Measurements of accessibility are not new (Wachs and Kumagai 1973; Vickerman 1974; Guers and van Wee 2004; Warade 2007), but the MEP metric significantly expands upon familiar (and popular) metrics such as walk, bike, and transit score (Walk Score® 2018; All Transit™ 2018). These current measures allow individuals to disparately assess whether an area is walkable, bike friendly, or well served by public transit based on the distances that can be traveled in various amounts of time using each of these modes. However, these calculations are proprietary and address only single modes. Also, these metrics often lack detailed information about overall performance, trip costs, and energy consumption.

Beyond location, distance, cost, and time, the MEP metric includes the capability to quantify energy consumption by fuel type. The "E" in MEP may be parameterized for energy, emissions, or any other negative externality associated with travel. MEP is the first of its kind to incorporate energy weighting in quantifying access to opportunities. The formulation presented herein primarily uses traditional factors for petroleum-based energy requirements similar to MPG, or MPG equivalents (such as MPGe with respect to electric vehicles). The MEP metric can be customized to either emissions or greenhouse gases, but energy use correlates highly to both, and it can be used as a surrogate.

The MEP metric measures opportunities within a time, cost, and energy budget. For example, it can indicate how many employment opportunities, health-care facilities, grocery stores, restaurants, parks, and entertainment destinations exist within 20 minutes of a location using different modes. The resulting numeric score provides a robust assessment of the quality of mobility provided to each traveler at a given location—regardless of whether travelers possess their own mode of personal transportation or use a bus, train, transportation network company (TNC) (e.g., Uber, Lyft), bike-share, or car-share. The MEP metric measures how well each mode—as well as a combination of modes—connects the traveler to a variety of opportunities. Additionally, the MEP methodology is open source and easily adaptable to include new modes as they emerge.

At the heart of the MEP metric are accessibility measures that build on existing accessibility theory and methodologies, assessing the number of jobs, goods, and service opportunities are available within prescribed travel times from a location. This approach is fundamentally a geospatial analysis, providing both a visual map for comparative analysis and a numeric score to baseline performance metrics. Data to support travel-time calculations and land use (i.e., available goods, services, and employment opportunities) are readily available using third-party travel data or outputs from regional travel demand models along with land-use data from cities, metropolitan planning organizations, or commercial entities. Isochrones—that is, lines on a map of a region showing what can be accessed within a given timeframe using a selected mode of travel—are calculated using readily available geospatial analysis techniques combined with the aforementioned data sources. For example, isochrones are constructed to reflect how far an individual can travel within 10, 20, 30, and 40 minutes from home by walking, biking, driving, or using public transit. Figure 1 shows the land-use map for the Denver metro region (Panel A) as well as a set of isochrones of 10-, 20-, 30-, and 40-minute travel time by driving mode from the center of downtown Denver (Panel B). These isochrones are constructed for each mode and each place (a 1×1 square kilometer pixel in the current analysis). Once the isochrones are developed, the MEP methodology quantifies the opportunity potential within the reachable area defined by the isochrones. For each isochrone area, the job opportunities, grocery stores, restaurants, recreation facilities, medical service providers, and more are enumerated. Land use is indexed to purpose (e.g., education, shopping-retail, health) as well as to job-opportunity potential (number of employees or jobs).

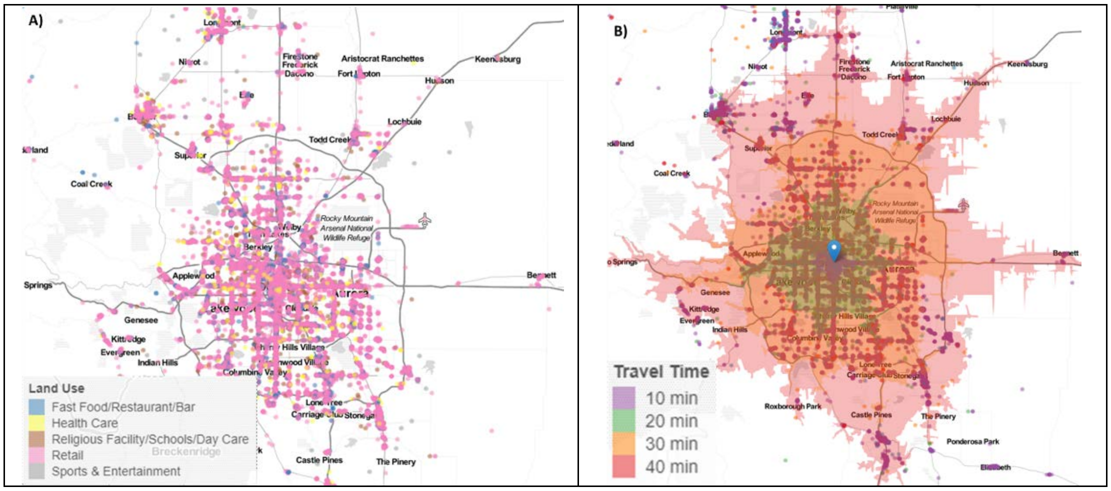


Figure 1. A) Land use map of Denver, CO; B) Isochrones of 10-, 20-, 30-, and 40-minute travel time by car from downtown Denver.

The quantity of each type of opportunity space is standardized (by activity proportionality constants and trip frequencies) and weighted by time, cost, and energy coefficients. The MEP equation is:

$$\mathrm{MEP}_i = \sum_k \sum_t (o_{ikt} - o_{ik(t-10)}) \cdot e^{M_{ikt}}$$

where o_{ikt} is the opportunity space measure, which represents the number of opportunities that can be reached by mode k in time t from location i; and M_{ikt} is further defined as

$$M_{ikt} = \alpha e_k + \beta t + \sigma c_k$$

where

M_{ikt} is the modal weighting factor for opportunities accessed by mode k with travel time t from location i

e_k is the energy intensity (kWh per passenger-mile) of mode k

t is travel time

c_k is the cost (dollar per passenger-mile) of using transportation mode k

α, β, and σ are weighing factors.

Modal weighting factors account for time, cost, and energy of each mode. For time weighting, destinations that are closer to a location are weighted higher that those that are farther. For example, having access to five grocery stores within 10 minutes is better than having access to the same within 30 minutes. α is the distance decay parameter that accommodates time weighting, and its value has been established in extensive accessibility research. Factors for cost and energy weighting reflect cost in terms of dollars and energy in terms of BTUs on a per passenger-mile basis. For example, having access to 10 shopping opportunities within 10 minutes of biking or walking is of more value than having access to the same number of shopping opportunities accessible by driving mode because driving is more expensive and uses more energy. Actual weighting values and example calculations are beyond the scope of this paper, but they are available in additional technical literature by the authors (Hou et al. 2019).

Note that the enumeration of the opportunity space—that is, counting the number of jobs, shopping, medical, education, and other opportunities—requires appropriate weighting. For example, suppose that traveling 10 minutes from a given location provides access to 50 job opportunities, two grocery stores, one shopping center, and two hospitals. A simple summation of these opportunities will create an incorrect assessment of meaningful opportunities accessible from that location. The MEP metric considers the frequency of different trip types as well as the relative spatial equivalency of different types of opportunities. To account for this, opportunities are standardized using a benchmarking measure as shown in the equation below:

$$o_{ikt} = \sum_j o_{ijkt} \cdot \frac{N^*}{N_j} \cdot \frac{f_j}{\sum_j f_j}$$

where

o_{ijkt} is the number of opportunities for activity j that can be accessed by mode k within the travel time threshold t from the ith pixel

N^* is the total number of benchmark opportunities across multiple cities (e.g., number of meal opportunities)

N_j is the total number of opportunities for activity j (e.g., number of shopping opportunities)

f_j is the frequency that people access opportunities of activity j.

The $\frac{N^*}{N_j}$ measure is based on data from a number of cities in the United States and provides a way to establish the spatial equivalencies of various types of opportunities. For example, the measure provides a way to convert access to 50 job opportunities, two grocery stores, one shopping center, and two hospitals into one single number.

Similarly, the activity engagement frequency ratio $(\frac{f_j}{\sum_j f_j})$ is implemented to acknowledge the relative differences in participating in different types of activities. A job is a more regular activity, so access to job opportunities is weighted higher than to, say, several movie theaters accessible from a given location because the latter is a less frequent activity. The activity engagement frequencies are obtained from the National Household Travel Survey (Oak Ridge National Laboratory 2018), but they can be augmented with specific local urban parameters as revealed by surveys and other data.

The analysis culminates into a MEP metric for a location, which can be aggregated to any desired geographical resolution by weighting with appropriate population-density measures. The basis of the MEP metric is the proximity and convenience of access to a variety of goods, services, and job opportunities that define a high quality of life reachable by various forms of mobility. Figure 2 (Panels A–C) shows the MEP metric (for all activities) in the Denver metropolitan region for different modal combinations.

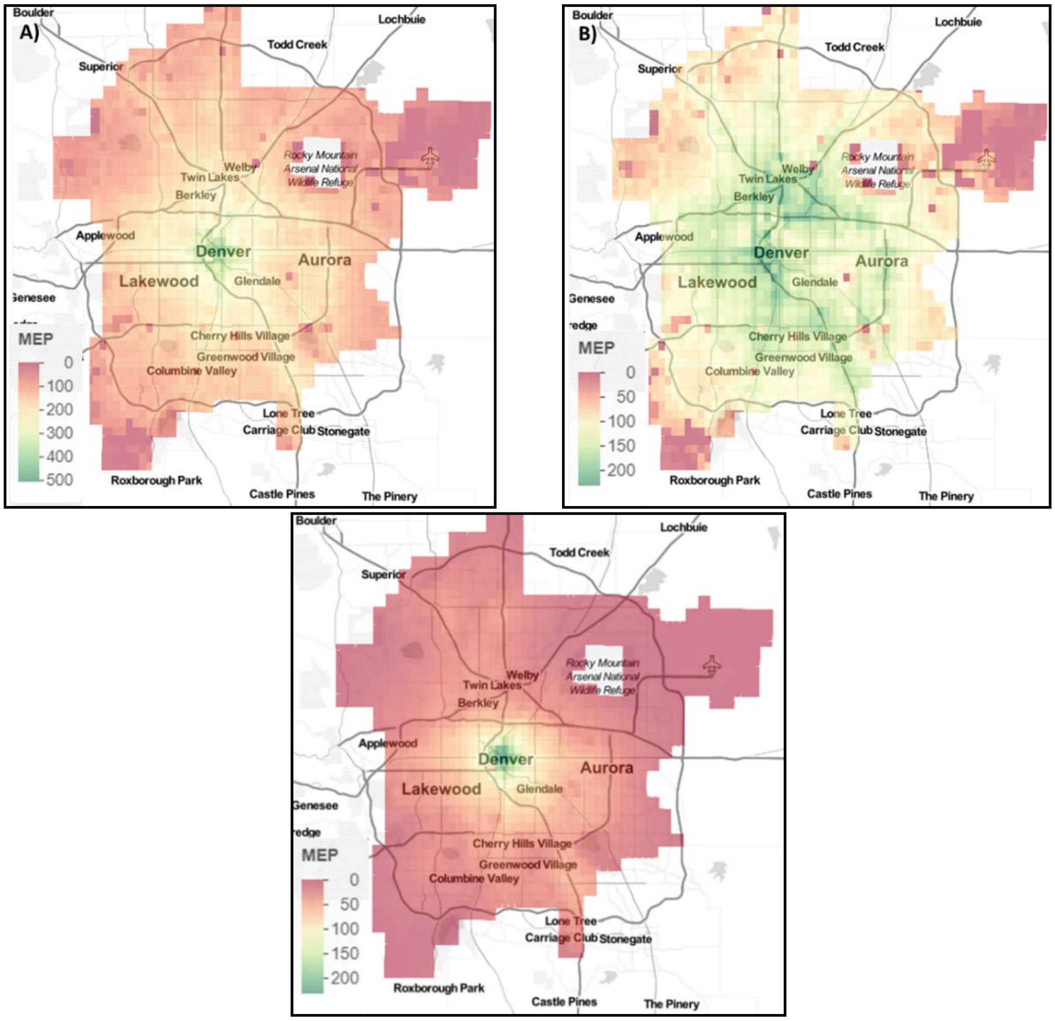


Figure 2. MEP maps by mode for Denver, CO: A) All modes; B) Car; C) Transit, walk, and bike combined

Each panel in Figure 2 reflects the relative magnitude of opportunities that can be accessed from a given location using a given mode. Red indicates that opportunity access from that pixel for that mode is less, whereas green indicates a greater access to opportunities using a given mode. It is clear that car mode provides the greatest access to opportunities across the city, which comes as no surprise because Denver, like many metropolitan cities in the United States, is an auto-dominant city. Panel C, which depicts the MEP metric for all modes (combined) except cars, shows greater access to opportunities closer to downtown and dwindles toward the suburbs, where opportunities are more sparsely spaced and transit availability is limited.

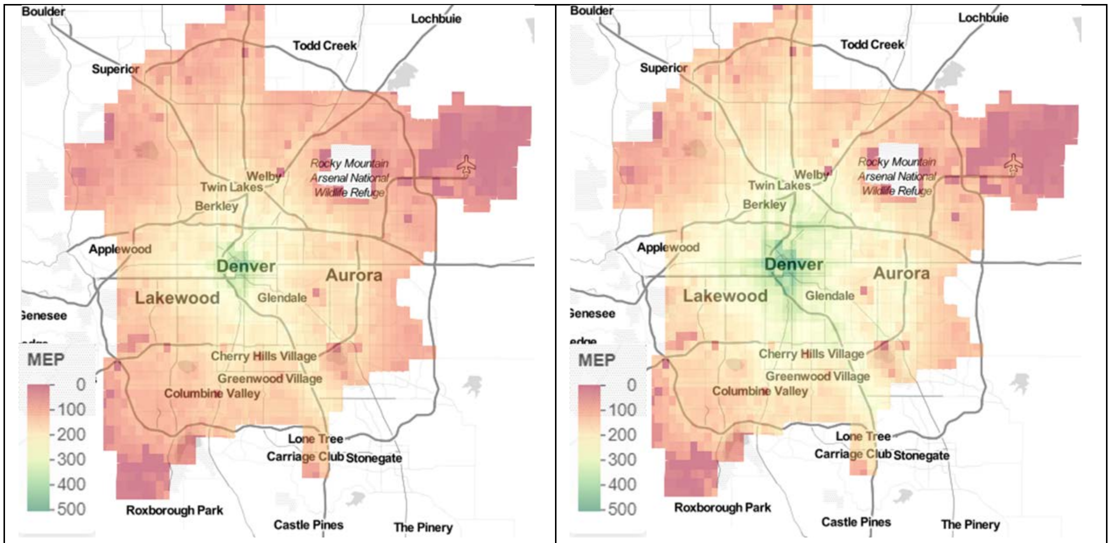
MEP APPLICATIONS

Tens of billions of dollars are expected to be expended in urban infrastructure investments and modernization upgrades in the coming years. Transportation officials will face many strategic decisions and complicated prioritization demands. Modeling efforts continue to evolve in accuracy, taking into account, for example, human behavior, congestion impacts, and end-times associated with parking hassle in urban areas. Decision makers lack appropriate metrics for applying to both measured data and simulation of alternative future transportation systems. The MEP metric provides transportation officials and city planners a means to fairly assess mobility, energy, and quality-of-life outcomes from new technologies that impact existing road systems, airports, curb fronts, parking needs, and overall urban infrastructure, thus helping planners to prioritize and inform investment decisions.

The MEP metric has been computed for a handful of U.S. cities based on available (not modeled) data to comprehensively assess the "quality of mobility" in these cities. Using the MEP metric, a city would be able to track fundamental changes in mobility over time as technology improves (e.g., greater electric vehicle penetration, automated vehicle adoption) and as new strategies to reduce congestion are implemented (e.g., enhanced transit, congestion road pricing, pedestrian/bike networks, deployment of automated electric shuttles). A city could also use MEP scores to aid in decision making. In summary, outputs of an urban travel demand model linked with the MEP metric will allow for more robust analysis, identify secondary technology impacts (e.g., increased congestion), and show how each of these decisions would affect the MEP score for the target neighborhood as well as the region.

NREL is in the process of linking the MEP methodology to sophisticated travel demand models, developing a module akin to the EPA MOVES (U.S. Environmental Protection Agency 2018), such that the results of any scenario analysis can be used to generate MEP metrics. The MEP module will also include an analytics package that can present the results visually at various scales and levels of aggregation. In the interim, NREL has developed a few potential scenarios using first-order approximations to show the capacity and utility of the MEP methodology. These scenarios include:

Greatly improved fuel economy: This scenario is representative of a future in which vehicles are much more efficient—such that the effective MPG (as compared to today's fleet) increases by 200%. The results of this scenario analysis applied to the Denver region are shown in Figure 3. Note that this neglects any secondary impacts that may occur such as induced travel or greater congestion.

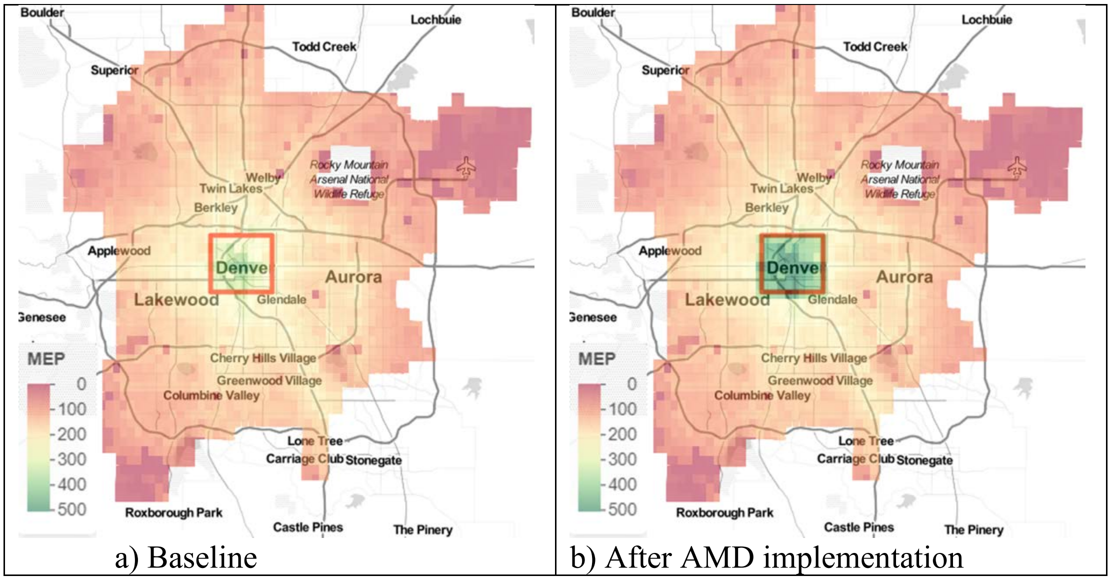


a) Baseline b) After improved vehicle efficiency

Figure 3. Scenario 1 – Impact on MEP due to greater vehicle efficiency.

The figure shows that improving vehicle efficiency increases MEP scores across most locations in a city. The overall MEP metric for the city in this scenario increased by 25%. The MEP score improvement in this scenario is not from an increase in opportunities but rather from an increase in driving mode energy efficiency.

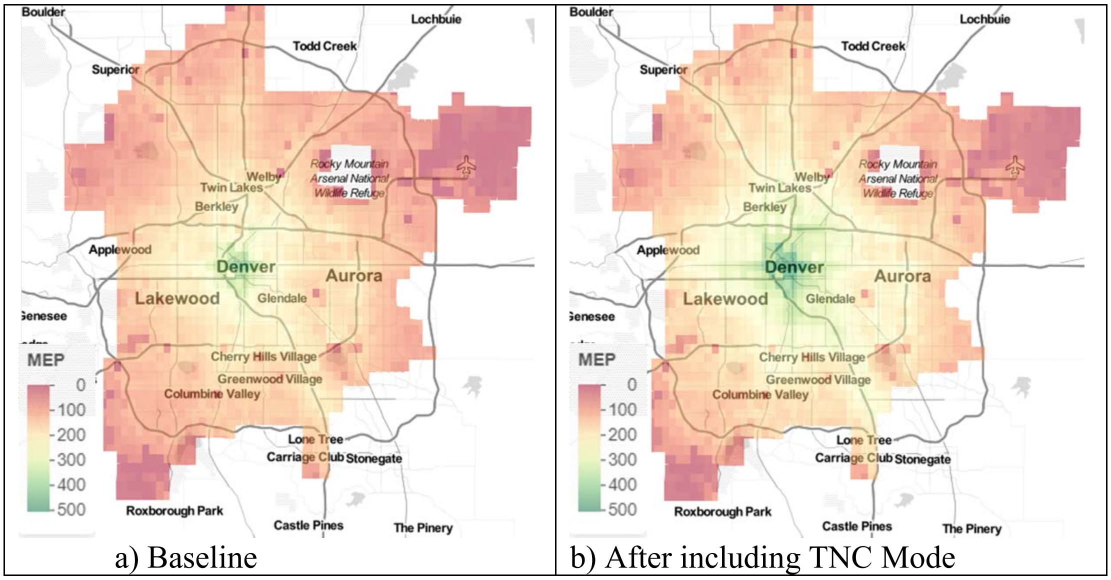
Implementation of shared automated mobility in a geo-fenced region: Adoption of automated mobility can be facilitated by deploying automated vehicles as a shared mode in a location of high trip density. In exploring this concept, NREL has coined the term Automated Mobility District (AMD). An AMD is a campus-sized implementation of connected/automated vehicle technology to realize the benefits of a fully electric, shared, automated mobility service within a confined region or district (Young et al. 2017). A geo-fenced region was selected in downtown Denver (shown with a red boundary in Figure 4), and hypothetical mobility improvements were introduced via enhancements in vehicle efficiency (mimicking a shared electric vehicle) as well as an increase in transit level of service. The objective was to showcase the utility of the MEP methodology in depicting “local” vs. global changes. Figure 4 shows that MEP scores increased only in the region where automated shared mobility is introduced whereas scores for the rest of the region remained the same. The overall MEP index for the city increased by 8% as a result of increased efficiency of transit mode in downtown Denver. This shows the powerful utility of the tool for city planners and policy makers, who can run a variety of scenario analyses for enhancing mobility in targeted areas and visualize the improvements through increased MEP scores. A benefit-to-cost analysis can then be conducted to select strategies that provide maximum mobility gains.



a) Baseline b) After AMD implementation

Figure 4. Scenario 2 – Implementation of an Automated Mobility District.

Inclusion of a new mode: TNCs (such as Uber, Lyft, and Via) are shown to increase mobility in many urban areas, providing convenient transportation accessed through a smart phone. A first-order approximation of TNC impact on MEP levels was modeled in a fashion similar to driving. Travel times were adjusted to account for the delay in waiting for a TNC pickup, costs were adjusted upward as typical of TNC use, and energy was adjusted to account for deadheading (vehicles circulating with no passenger). This initial approximation does not account for any induced congestion as a result of the introduction of this new mode. Figure 5 shows the MEP maps for Denver before and after including TNCs in the MEP calculation. It can be observed from the figures that the MEP scores improved across the Denver metro region when the TNC mode was included in the calculation, though note that the change is depicted as a simple addition to existing modal availability.



a) Baseline b) After including TNC Mode

Figure 5. Scenario 3 – Inclusion of a TNC mode in MEP computation.

This analysis was carried out in six metropolitan areas in addition to Denver. The improvement in the MEP scores ranged from 18%–23%, with an average improvement of 20%. The topic of appropriate accommodation of additional modes in the MEP computation (mode addition vs. mode displacement) is currently being analyzed by NREL researchers. Note that in all the scenario analyses mentioned above, assumptions were made to show first-order effects in MEP scores due to technological advancements or transportation investments. Coupling the MEP calculations with agent-based travel microsimulation models can fully capture all effects, not just primary impacts such as energy intensity, but also, impacts of adoption rates, induced (or reduced) congestion, and other secondary and tertiary impacts that can arise from these scenarios.

CONCLUSIONS AND DISCUSSION

New mobility choices will have critical impacts on the functioning of metropolitan areas and decision making for transportation, energy use, and infrastructure. Communities of the future will need to measure the quality of the multitude of modal options available to their citizens, as well as move beyond single-mode, vehicle-specific, or infrastructure-specific metrics such as MPG, volume-to-capacity ratios, or vehicle-miles traveled.

A methodology for a comprehensive metric labeled the Mobility Energy Productivity (MEP) metric is presented in this paper. The MEP metric quantifies the quality of mobility that a location offers, weighted by time, energy, and affordability aspects of the modes that provide mobility. The MEP metric will allow communities to disaggregate the score to isolate the impacts of certain mobility options at specific locations or among certain subpopulations and track progress over time, as well as aggregate upward to reflect an overall dashboard of fundamental impacts citywide.

The MEP metric offers a sophisticated tool to characterize, measure, and manage the movement of people and goods within a given location or region. The ability to quantify mobility using the MEP metric has the potential to create more livable and sustainable communities that offer transportation choices that are affordable, accessible, and lead to higher quality of life for citizens. For this reason, NREL is partnering with ASCE to offer this metric and its framework as a standard measure for use in smart cities. This effort will focus on identifying baseline parameters to compute the metric so that cities across the United States and beyond will have a common standard to quantify and track the quality of mobility in their cities. Although the basic framework is developed, work is in progress to add refinements for socio-economic changes, accurate end-time representation (such as parking delays), and adaptation for additional modes. NREL is creating a MEP module, similar in concept to the standardized calculation framework provided by EPA MOVES (U.S. Environmental Protection Agency 2018), that can work with existing urban transportation models at any level of sophistication (from traditional four-step models to modern activity-based models). This approach enables the modeled results to be viewed through the MEP lens and facilitates objective quantification of sustainable urban mobility concepts.

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