THE CHALLENGES OF MEASURING TRANSPORTATION EFFICIENCY

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ABSTRACT

In the US, concerns about dependence on oil (foreign oil in particular) have intensified and the transportation sector has garnered increased attention for its contribution to global warming. In response to these concerns, there is an increasing focus on the efficiency of our transportation systems. The objectives of this paper are to provide a framework for defining transportation efficiency (TE), highlight the ambiguities present in the transportation-research literature and in public policy, and describe the challenges that come with attempts to comprehensively measure TE. Of particular concern are the many studies which simply describe policy strategies associated with TE, without attempting to comprehensively define or measure it. Defining "transportation efficiency" as the maximization of *services* at the lowest possible *cost* will require that a variety of costs and service variables be assimilated into a comprehensive measurement tool. Such a tool could be used to find a TE index for temporal and operation TE comparisons. However, temporal applications are susceptible to rebound effects and operational comparisons are susceptible to shifting effects. Few assimilative measures of TE have been found which even attempt to deal with these potential sources of error. Better models are needed to adequately assimilate a wide variety of economic, environmental, human, energy, and operational variables on TE, and to assess rebound and shifting effects.

INTRODUCTION

Some economists feel that the global peak for oil production has passed, and that past trends in energy prices are no longer reliable (Rubin, 2009). Increasing oil prices will have an effect on many areas of the world economy, since oil accounts for approximately 35% of the world's primary energy supply (IEA, 2007). No economic sector is more dependent on oil, though, than transportation. Nearly 95% of the energy for transportation worldwide comes from oil (IEA, 2007). In the United States, where per-capita transportation demand is highest, concerns about dependence on oil (foreign oil in particular) have intensified. In fact, nearly 2/3 of all US oil use is for transportation (DOE, 2009). In addition, volatile oil prices may have played a significant role in the current recession in the US. In August of 2008, when gasoline prices reached $4.00 per gallon, vehicle-miles of travel in the US were down 15 million from August 2007 – the largest drop ever. Some economists argue that the next demand-supply imbalance will bring gasoline prices closer to $6.00 per gallon in the US (Rubin, 2009). The transportation sector has also garnered increased attention for its contribution to global warming. This sector was responsible for 28% of all greenhouse gas (GHG) emissions in the US in 2004, up from about 25% in 1990 (Davies et al, 2007).

In response to these concerns, there is an increasing focus on the efficiency of our transportation systems. In fact, two of the most significant pieces of federal transportation policy in the post-Interstate era (ISTEA in 1991 and SAFETEA-LU in 2005) have included provisions for improved efficiency in transportation in the United States (USDOT, 2009). In the state of California, strategies to reduce greenhouse gas (GHG) emissions under the landmark California Global Warming Solutions Act of 2006 included transportation-specific measures – cleaner cars and trucks, low-carbon fuels, and Smart Growth to reduce trip distances (Wanless et al, 2007).

The use of the term "transportation efficiency", or TE, in the research literature is often poorly defined, even though some of the strategies associated with it have been explored in depth. Most of these *associated* strategies involve transportation-energy efficiency, which is closely related to TE but is not identical, since TE could also include generalized costs related to personal-choice, environmental impacts and operations. In addition, most of these investigations have failed to start with a comprehensive definition of TE, with which to derive an effective measurement tool. It will be essential when designing a new policy or program aimed at improved TE, to develop an *assimilative* metric, which assimilates a variety of data, to demonstrate comprehensively that TE has been improved or that the specific TE of relevance to a given circumstance has been improved.

The objectives of this paper are to highlight the ambiguities present in the transportation-research literature and in public policy, to provide a framework for defining TE, and, most importantly, to describe the challenges that come with attempts to comprehensively measure TE. Of particular importance to the effective measurement of TE are the paradoxical relationships between efficiency gains and demand patterns (rebound), and between apparent and realized efficiency gains (shifting). Any effective measurement of TE must account for these potential sources of error in order to accurately predict the true gain in a given efficiency measure as a result of a specific policy measure.

DEFINING TRANSPORTATION EFFICIENCY

Amidst the increased attention to TE is a growing ambiguity in the use of the term. Many studies take TE to be synonymous for a specific improvement measure, such as increased vehicle occupancy rates (Moudon et al, 2005). Others expect TE to be synonymous with measures intended to decrease GHG emissions (Barth et al, 2006). At the policy level, the term is used in the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) as a synonym for cost efficiency (USDOT, 2009). Cost efficiency has been defined as maximizing the benefit-cost ratio when choosing amongst a variety of transportation modes (Young et al, 2002). The act sets forth guidelines which expedite the permitting, design, and construction processes for major transportation projects.

Then in the 2005 Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), efficiency refers to the durability of transportation improvements. Although the act does not specifically define TE, the term is used extensively, and an overview statement (FHWA, 2005) suggests a definition in terms of longer-lasting transportation infrastructure, presumably in response to frustrations with aging infrastructure. The overview later suggests a relationship between TE and improved planning and streamlined construction processes.

Many studies of TE in the research literature are targeted either at transportation *operations* efficiency or transportation *energy* efficiency, but they often set strategies for improving and measuring TE without explicitly providing a fundamental definition beforehand. Defining "transportation efficiency" as the maximization of *services* at the lowest possible *cost* will require that a variety of costs and service measures be included in a comprehensive measurement tool. It will then be necessary to assess which costs and services are included in the TE measurement. This assessment will depend in part on whether the efficiency of the transportation system's *operation* is being tested, or whether its *energy* efficiency is being tested. An evaluation of transportation-energy efficiency may need only include variables related to energy resources, whereas a comprehensive measure of transportation operations efficiency might need to include many other types of stakeholder-specific variables as well. Economic efficiency measures involve yet another subset of variables.

The goals of maximizing the operating efficiency and maximizing the energy efficiency of a transportation system may include very different priorities. There are many ways that these two goals are coincident, but in other ways they are not. The interests of separate stakeholder groups (planners, operators, users, and community members) often lead to different priorities for a transportation system. Planners and community members will have an interest in those aspects of the transportation system which contribute to improved resource utilization and environmental protection including air, water, and noise pollution mitigation. Improved resource utilization could include more efficient uses of energy, land, and human resources. Operators and users are more interested in costs and benefits specifically associated with transportation infrastructure such as accessibility, reliability, congestion, safety, and convenience. Utility and econometric methods have been developed to assimilate multiple variables into a measurable TE index. These indices are typically measured operationally or temporally for comparison of two or more regions, modes, or scenarios.

Differing priorities may also result from the type of application the TE index is serving. TE indices are used in two main application areas – temporal comparisons of TE-improvement and operational TE comparisons of two or more different transportation systems.

From the planner's perspective, a state transportation agency may want to know which of its major municipalities has the most efficient transportation operation, and which has the least. This knowledge can be used to support funding allocations for TE improvements. A normalized TE index could be especially useful if the systems being compared are complex and of different scales, making the comparison non-intuitive. In this type of operational-efficiency application, TE is measured using inputs for two or more separate transportation systems, then TE indices are compared to determine which system is more efficient. Sensitivity analyses can be used to determine the variables that are most critical to the TE index, providing guidance on how TE can be improved. Cheon (2008) performs an operations-TE comparison, using data envelopment analysis (DEA) to develop TE indices for each of the world's top 75 container-shipping ports.

The second type of application is used to evaluate the effectiveness of an effort to improve TE – a "before and after" temporal comparison. In this type of temporal TE-improvement application, TE is measured using inputs for one transportation systems before and after a policy has been implemented. The TE indices are then compared to determine if the efficiency of the transportation system has improved as a result of the policy implementation. Barker and Rubin (2007) demonstrate a macroeconomic TE-improvement application. In their model, variables related to transportation-energy efficiency are included to assess the ability of various policy measures at improving TE.

In order for a TE measurement to be effective in either of these types of applications, ambiguities in the definition of TE must be avoided, and the costs and services being considered must be clearly identified. The goals and the boundaries of the TE measurement study must also be clearly defined.

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The ultimate challenge, then, is to develop a TE measurement tool which can be used for operational and temporal applications to measure the effectiveness of regulatory policies. In complex transportation systems, the relative effects of different variables on TE are not intuitive, so they must be assimilated into an index. An abstract measurement such as a TE index is going to be affected directly by some variables and indirectly by others.

TE appears in a variety of contexts within the research literature, the private-industry literature, and regulatory policy, and its use is not consistent within these contexts, but often pertains to a particular set of strategies expected to lead to improved TE. The TE being assessed in these studies is often not distinguished as transportation-energy efficiency or transportation-operations efficiency when it is one or the other that is being sought. These strategies do not in themselves constitute an assimilated index. Instead, they are simply general strategies that have been *associated* with TE. Without assimilating a wide variety of variables, though, each of these strategies falls short of the goal of comprehensively assessing TE. Taken together, though, these studies provide an exhaustive list of the many cost and service variables which are a substantive part of TE.

There are a few examples in the research literature of the use of an effective measurement tool, such as total generalized cost, utility, or an abstract TE index. These examples constitute truly *assimilative* measures of TE. Even with a comprehensive measure, however, there are challenges to be overcome in the application. Temporal and operational applications are susceptible to errors due to inadequate boundary-selection and inexplicit goal-setting. A truly effective TE index will account for the effects of "rebound" and "shifting" in its application

In this section, the *associated* strategies are discussed, and a list of the many measurement variables included is provided. Then the *assimilative* measures of TE and their applications are discussed, followed by an analysis of the many possibilities for error, even with assimilative TE measurements.

Strategies *Associated* with Transportation Efficiency

The most common use of the phrase "transportation efficiency" equates it with the following strategies which are aimed at increasing TE:

- Capacity Utilization
- Emissions-Reduction
- Land-Use Improvement
- Operational and Modal Coordination

However, when these uses lack a definition of the type of TE being measured, and the specific measurement tool being used, they can only be considered strategies *associated* with TE.

Capacity Utilization Strategies Associated with Transportation Efficiency. In planning contexts, strategies most commonly associated with TE are capacity-utilization strategies. Capacity-utilization strategies are those which seek to maximize the “load” on a vehicle, network link, or transportation system, relative to its capacity. The implication in these studies is that the most efficient use of a transport vehicle, a network link, or an entire transportation system occurs at or near its capacity. Most of the improvement strategies by public agencies reviewed for this paper target vehicle-occupancy rates. The expectation is that increased vehicle-occupancy rates, particularly for private vehicles, will satisfy current vehicle demand with fewer vehicles (Barth and Shaheen, 2002). Other indirect benefits noted include lowered transportation costs, energy use, and emissions, and increased transit ridership. All of these benefits are expected to result from increasing private-vehicle occupancy rates from shared-use vehicle systems, such as car sharing organizations, station-car systems, and carpooling-support systems. Other studies set the goal of simply eliminating or decreasing single-occupancy vehicle (SOV) trips to achieve gains in TE (Moudon et al, 2005).

A strategy strongly associated with TE in private industry is the maximization of capacity-utilization in freight. Higher weight limits for freight trucks on federal highways and interstates are TE measures expected to conserve fuel, reduce emissions, and increase productivity (AgTEC, 2009). Speedier border crossings have also been the focus of truck-freight TE improvements (DMG, Inc., 1999). This type of approach is also advocated by TRB in a special report on truck freight (TRB, 2002). However, critics of this approach to increasing truck capacities point to the decrease in rail freight that would likely result from an increase in truck freight capacity (McCullough, 2003). The implication here is that moving freight transport from a more efficient mode (rail) to a less efficient mode (trucking, albeit with increased capacity) benefits only the truck freight carrier. Consistent with this interpretation, the Chicago Region Environmental and Transportation Efficiency (CREATE) partnership is focused primarily on freight rail improvements to increase TE, presumably because of a focus on lower energy use AND higher productivity for industry (CREATE, 2009).

Other large-vehicle operators measure TE as the operation of motor vehicles such as trucks and buses at or above their capacity, attempting to avoid empty return-trips (NJDoE, 2009). There are also studies that evaluate the relative benefits of adding high-occupancy vehicle (HOV) or high-occupancy toll (HOT) lanes and use the resulting capacity-utilization of the roadway and the vehicles as a means for comparing TE for various options (Dahlgren, 2002).

The efficiencies of specific road systems are often evaluated in terms of their capacity-utilization. The capacity-utilization of a road system refers to the vehicle flow-rate that it carries relative to the maximum vehicle flow-rate for the roadway. Studies exploring new applications of intelligent transportation systems (ITS) acknowledge the competing objectives of increasing roadway capacity-utilization and decreasing travel-time delays (Xin et al, 2006). Others contend that helping traffic flow smoothly at its free-flow speed will have a positive impact on efficiency (CS, 2009).

In most of these studies strategies associated with capacity utilization are expected to lead to improved TE. What is strongly lacking is an initial, comprehensive description of which factors go into the measurement of TE, and specifically how these strategies will improve it.

Emissions-Reduction Strategies Associated with Transportation Efficiency. Other examples in the literature exist for TE as synonymous with strategies to reduce vehicle emissions, while providing the same level of service. California's stated "Steps Toward Reducing GHG Emissions" are frequently cited or borrowed as substitute strategies for improving TE (Barth et al, 2006). These strategies include (1) reducing vehicle-miles travelled (VMTs), (2) increasing vehicle engine efficiency (mpg), and (3) increasing the use of alternative fuels. The state of California also proposes a package of policies designed around these strategies, which include non-transportation strategies to increase energy efficiency: energy efficiency, renewable energy, and cleaner power plants (Wanless et al, 2007).

Several states have adopted this framework as a way to increase TE (Gallivan et al, 2008), or have adopted TE as a way to achieve emissions reductions (VTrans, 2008). Vermont is currently undertaking its second update to a Comprehensive Energy Plan, in which transportation efficiency is assumed to pertain to either vehicle engine efficiency or to vehicle engine emissions-reductions (VDPS, 2008).

Other specific strategies to reduce emissions are prevalent in the literature. Intelligent transportation system (ITS) components are often aimed at reducing emissions, as are efforts to control driver behavior and speed. These types of efforts are associated with transportation efficiency in new research focused on GHG reductions (CS, 2009). These studies expect that strategies associated with emissions reductions are also going to lead to improved TE. Again, however, they lack is a comprehensive description of TE, and a measurement to specifically demonstrate how these strategies will improve it.

Land-Use Improvement Strategies Associated with Transportation Efficiency. The following categories have been put forth in the literature as land-use strategies that are expected to lead to increased TE (Kavage et al, 2005):

1. Compact development
2. Mixed-use development
3. Connectivity
4. Pedestrian environment / safety
5. Limited vehicle parking availability
6. Affordable housing

Others have considered the effect of land-use control strategies on TE (Johnston, 2006; Yuan and Lu, 2009; Moudon et al, 2005; Hagler, 2008).

These measures are expected to put people closer to the services they need, decreasing the distance of vehicle trips, or allowing trips to be completed with a more energy-efficient mode which emits less, such as transit or biking. Better connectivity of road and transit networks is expected to create a more robust road network, preventing wasted travel time. These measures are also expected to increase the appeal of more efficient, alternate modes of transport such as walking or biking, presumably displacing vehicle trips. In spite of these expectations, these studies often lack an effective definition of the specific TE being measured, and how these strategies are going to improve it.

Operational and Modal Coordination Strategies Associated with Transportation Efficiency. Government agencies seeking to improve accessibility in rural areas promote the use of coordination to improve efficiency for a transportation mode by addressing (Burkhardt, 2005) factors like duplicative transportation services, decentralized operation, lack of cooperation or communication, and the lack of a comprehensive plan. Coordination measures aimed at improving TE also include those intended to help different modes of transport work together by integrating modal planning (Giuliano, 2007). Modal coordination entails adjusting the working parameters (timing, accessibility, cost, comfort) of each transportation mode (auto, train, airplane, subway, bus, right-of-way transit, bicycle, and pedestrian) to meet the overall transportation plan. The overall transportation plan includes the intended use (in persons per hour) for each mode to achieve optimization of the transportation system for all (Vuchic, 1999). Coordinating those modes of transport can decrease total travel times significantly, when waits and walks between modes are included (Veolia, 2009). Multi-modal coordination is also becoming a national priority in the United States. As described by Lowy (2009), the new Transportation and Infrastructure Committee of the US House of Representatives has introduced a $500 billion bill to "connect different modes of transportation…so they work as a single system…"

Supply-chain efficiency is also focused on improving multi-modal coordination. Private industries often define TE as supply-chain efficiency, which in turn is expected to result in emissions and waste reductions (HONDA, 2009; Balanced Scorecard, 2009). Ironically, an automobile manufacturer's efforts at improving TE focus on its manufacturing supply-chain and say nothing about making more efficient vehicles (HONDA, 2009). For large, complex supply-chains, efficiencies gained in transportation translate directly into cost efficiencies. Transportation occupies the highest percentage of logistics costs in the average supply chain, with inventory-carrying and warehousing close behind (Establish, Inc., 2003). In addition, the increasing implementation of "just-in-time delivery" and "pull" types of supply chain strategies and increasingly multi-modal globalization has increased the ratio of transit time to total lead time in the supply chain, making transportation coordination even more critical (GSCA, 2005).

Modal coordination in transportation can be considered in the extreme case by considering the replacement of all transport vehicles with an "intelligent-vehicle". Investigations of the many applications for ITS include the use of standardized (intelligent) vehicles to coordinate all transport movements (Wang et al, 2009). The assumption here (possibly unrealistic) is that all modes are replaced with a single Cybernetic Transportation System, whose individual vehicles are centrally controlled and perfectly efficient.

These publications and studies attest to the growing importance of operational and modal coordination in our often disjointed, decentralized transportation systems. However, most of them fail to provide a comprehensive definition of the TE being improved, and what measures will be used to prove that it has been improved.

TE Measurement Variables. In spite of the shortcomings of many of the studies which consider strategies associated with TE, this group of studies taken together provides a comprehensive list of all the measurement variables that are considered when efficiency improvements are sought. Table 1 contains all of the variables that appeared in the *associated* strategies, along with other relevant variables added by the authors. In the table, the variables have been separated into “costs” and “services”, and stratified by type. “Cost” variables are those that are undesirable and minimized to achieve improvements in TE, whereas “service” variables are those that are maximized to improve TE. The variable “types” are relevant to the difference stakeholder groups involved in the use and planning of our transportation systems, and the type of TE that will be measured.

TABLE 1 Measurement Variables Related to TE

Variable Type	“Cost” Variables	“Service” Variables
Economic	Prices for the user[5,1] Prices for the operator[11]	Cost savings[1] Economic development and productivity[2]
Environmental	Carbon emitted per mile travelled[1] GHG emissions[1] Noise[11] Fuel used per mile travelled[1]	Reduced impact on the environment [1]
Energy	BTUs per mile travelled[1] Energy used per capita[10] Energy used per person-mile of travel[11] Total energy use[10]	Decreased dependence on fossil fuels[8] Robust energy portfolio[10]
Human	Fatality[10] Serious injury[10]	Improved safety[3] Basic human needs met[11] All travel demand satisfied[11]
Operations	Time spent travelling[5] Time wasted in congested travel[1]	Lower vehicle-miles travelled[7] Fewer trips[11] Coordination between modes[9] Access[10] Choice[3] Speed[1] Convenience[6] Reliability[6] Increased vehicle capacity use[4] Level-of-Service (LOS)[5]

Citations

1. Manikonda et al, 2001
2. Southworth et al, 2004
3. Kavage et al, 2005
4. Barth et al, 2004
5. Moudon et al, 2005
6. Hagler, 2008
7. Johnston, 2006
8. Rubin, 2009
9. Vuchic, 1999
10. VDPS, 1998
11. Added by the authors

Assimilative Measures of Transportation Efficiency

There are more comprehensive efforts in the literature to define and measure the efficiency of transportation-energy, or of a transportation-operation, which address the shortcomings described above. These efforts constitute *assimilative* measures of TE.

Barker and Rubin (2007) develop a macroeconomic tool which describes TE as energy efficiency in transportation, or lower energy-use for the same level of service. In this study, variables related to economic productivity, fuel prices, and energy demand are assimilated into a model. The study finds that pricing strategies are critical to the success of TE-improvement policies, and that revenues gained from fuel duties must be recycled into the economy for the improvements to be maximized.

In macroeconomic applications to supply-chain, TE is critical since supply-chains typically rely heavily on transportation costs. Efficiencies in the supply-chain coincide with efficiencies in transportation. DEA is often used to draw an efficiency relationship between generalized input/output variables in the supply-chain. DEA is an approach that extends a traditional efficiency measurement in operations research, generalizing the single-input, single-output ratio measure of the efficiency of a single decision-making unit (DMU) to a multiple-inputs / multiple-outputs setting (Cheon, 2008). The DEA measurement tool can also be applied to a specific transportation-operation. In public transport, each municipality can be considered as a DMU, and their relative levels of inefficiency can be compared (Sanchez, 2009). For abstracted measures of this type, the selection and weighting of variables becomes critically important, as does the quality of the data used in the model. Sanchez (2009) uses number of staff, fuel consumption, and number of vehicles in the fleet as inputs, and vehicle-miles, vehicle capacity, hours of service, frequency of service, comfort, number of stops per route (accessibility), and safety as outputs to compare the efficiencies of public transportation systems in Spain.

Another measure of TE identifies maximum utility versus distance of travel, with utility defined in terms of speed, cost, convenience, and reliability (Hagler, 2008). Distance of travel is measured from a city center, and the resulting TE (measured as utility) is plotted for auto, rail, and air modes. A similar definition suggests that TE is an optimization which seeks to maximize choice and number of persons served, while minimizing cost and/or time spent traveling (Moudon et al, 2005). And a third utility-based definition ranks cities by the efficiency of their transportation systems, using a utility measure to assimilate variables related to population density, mode share, vehicle usage, road length, speed and v/c ratio (Yuan and Lu, 2009).

Challenges with the Application of Assimilative Measures of TE

Complications are inherent to even well-planned, assimilative measures of TE. Temporal applications are particularly susceptible to missing the effects of “rebound” on a particular TE-improvement strategy. Applications involving operational comparisons of TE are susceptible to “shifting” effects, particularly when too few variables are considered, or when the boundaries of the study are too limited.

Challenges Presented by the “Rebound” Effect on Temporal Applications. As efficiency gains bring users’ costs down, standard economic theory dictates that price will go down. Users end up getting more energy for the same price, encouraging them to use more and counteracting the benefits of the initial efficiency gain. This relationship between efficiency gains and demand was initially observed over a century ago. Following the advent of the steam engine, coal consumption initially dropped, and then rose dramatically in the next 30 years (Rubin, 2009). This phenomenon has come to be known as the “rebound effect” (Small and Van Dender, 2005).

The rebound effect can apply to efficiency in any economic realm, including transportation. In standard transportation-demand models, transportation-capacity is represented as economic supply and the users’ demand for travel as the economic demand. Travel time is the primary cost incurred by the user. Traffic congestion tends to maintain equilibrium. It has been observed that if road capacity (supply) increases, the number of trips (demand) using the road also increases until congestion limits further traffic growth. The additional travel is called “generated traffic” or “induced demand”. Generated traffic reduces the benefits of capacity expansion and increases many external costs, such as total emissions and total energy usage (Litman, 2009).

A critical factor in this observation is travel time, which, for road users, is the primary "cost" of travel. It would be possible to derive a "generalized cost" by including the vehicle costs, fuels costs, and indirect costs to the environment, but we would observe that the value of these costs relative to travel time is insignificant. The reason for this insignificance is that, unless oil prices are significantly higher, road-travel in the US is effectively free. So private-vehicle users make decisions based on travel time when oil prices are low. Increases in capacity initially cause a corresponding decrease in travel time. This improvement in travel time on the new road has two effects on the flow. The first is that it diverts traffic from less desirable times of day, routes, and destinations. Second, as predicted by the rebound effect, it induces new vehicle travel from other modes – users who are now willing to make the trip by car when in the past they were not. Further support for this phenomenon in the transportation realm is evidence that people tend to economically optimize their total daily travel time, making subtle increases or decreases to maintain what they find acceptable (Hubert and Toint, 2006). The implication here is that as their travel time for one activity decreases, users will find other activities to travel to in order to fill the free time. Inability to pro-actively measure this unsatisfied demand will confound efforts to develop measurements of TE.

Without acknowledging these types of effects on TE, costly measures to improve TE may fall short, or have unintended negative consequences. Considering the potential rebound effects on TE improvements, the *associated* strategies set forth previously are revisited below to explore the possibility of induced demand, or rebound, reducing or eliminating efficiency gains.

Increased capacity utilization of motor vehicles may not lead to improved TE if rebound effects are present. As suggested by McCullough (2003), filling available capacity in one type of vehicle may be drawing demand from another more efficient type of transport, or from a user who would not have made the trip at all. It must be shown that there is demand for walking, biking, and carpooling amongst the users currently making single-occupancy-vehicle (SOV) trips in order for increased vehicle occupancy to lead directly to improved TE.

The rebound effect would suggest that encouraging carpooling will not necessarily lead to improved TE. Increasing vehicle occupancy is effectively increasing the realized capacity of the road system or increasing the efficiency of the vehicle. This improvement in capacity will decrease generalized costs of travel to the users, and might encourage them to increase use.

Emissions-reduction strategies, which often include efforts to more efficiently use fuel, are very susceptible to rebound. When increased oil prices in the 1970s spurred increases in the fuel efficiency of motor vehicles, the average mileage per gallon of gasoline improved. Since 1980, the average fuel efficiency of a motor vehicle manufactured in the United States has improved 30%. However, the fuel used per vehicle during that time period did not improve, presumably because drivers used the savings to buy more fuel and drive more miles (Rubin, 2009). Today, efforts to encourage reductions in GHG emissions are likely to suffer the same fate. Even if the true costs of a vehicle's GHG emissions are collected at the pump, it is possible that vehicles with improved emission-capabilities will allow driving behavior to remain constant. In this case, emissions would improve, but not as much as the engine-emission reduction.

Land-use improvements such as compact development, mixed-use development, and affordable housing may also be susceptible to rebound effects. These types of land-use controls can make a downtown area more attractive as a destination and as a living environment, attracting more residents who don't work there. This attractiveness will increase the use of motor vehicles and the distance traveled as these new residents reverse-commute to other sub-regions outside of the city center. In fact, studies show that land use and transit policies have very little effect on TE unless they are supported by aggressive pricing policies (Johnston, 2006). Affordable housing will only reduce VMTs if matching job opportunities and affordable services are present near the affordable housing. If this is not the case, then including affordable housing in a new development scheme may increase VMTs as residents need to travel farther to work or to reach affordable services.

Scenario modeling and GIS evaluation tools have been used to assess the effectiveness of land-use strategies on TE. The median reduction in VMTs for 31 20-year scenarios was only 2.3% (Johnston, 2006). This figure is likely within the margin of error of the transportation models used, and is also within the margin of potential rebound effects, which can counteract efficiency gains as much as 45% (Rubin, 2009). This margin implies that unless a proposed land-use strategy should be evaluated carefully to ensure that its expected improvements in TE are worth the cost of implementation.

Better connectivity of road and transit networks and better pedestrian environments may encourage walking or biking, but these trips may not replace vehicle trips. Instead, these improvements can lead to increased demand for trips to a more attractive downtown area, having a similar effect as compact and mixed-use development. Increased pedestrian traffic in downtown areas has been shown to increase the attractiveness of a neighborhood for all trips, even by motor vehicle. In fact, a study of pedestrian traffic in the most desirable areas of downtown Washington DC showed that more than half were not residents of the city (GA, 2008). Latent demand for walking and/or biking may be satisfied, but vehicle travel can remain the same or increase.

Challenges Presented by the "Shifting" Effect on Operational Applications. Additional complications are inherent to measurements involving transportation-operation comparisons, particularly when too few variables are considered, or when the boundaries of the study are too limited. The effects of these types of errors can be to shift the transportation "costs" elsewhere. When this "shifting" effect occurs, efficiency gains for a region or mode are offset by efficiency losses elsewhere, as when increased truck freight efficiency decreases rail freight efficiency (McCullough, 2003).

The shifting effect applies more specifically to operational efficiency applications, whereas the rebound effect applies to temporal applications. Without looking for potential shifting effects on TE, measures to improve TE may appear successful, when in fact the inadequate selection of variables or the inadequate definition of study boundaries is masking TE losses.

For the capacity-utilization concept, shifting can occur for example if carpooling from “rally points” outside the downtown area simply displace congestion from downtown to the edge of the city. In this way, efficiency gains in the downtown area appear promising, but overall congestion for the greater metropolitan area has not improved. An analogy is provided in the supply-chain sector to squeezing a balloon — where carbon reductions achieved by a business actually increase the carbon footprint of its suppliers or customers (Fenwick, 2009). The idea is that switching a manufacturing process to the use of more environmentally-friendly materials may not improve the overall efficiency of the entire supply-chain if these materials must be sourced farther away, since generalized transportation costs will be increased. The net result may be a more eco-friendly product which has a greater adverse environmental impact.

Amongst land-use concepts, mixed-use development-patterns may decrease the distance of most vehicle trips, but increase levels of congestion in downtown areas if other modes are not available. The increasing congestion in the downtown areas can lead to increased vehicle-hours of travel (VHTs), even as VMTs are reduced, due to congestion. VHT-increases may then lead to increases in total emissions. Limiting vehicle parking and increasing bike parking, a land use strategy suggested by Kavage et al (2005), may not lead to fewer vehicle trips and higher-occupancy rates in motor vehicles. Limited motor vehicle parking may increase congestion in a downtown area as new users and visitors fail to find parking where they expect it.

These types of challenges must be faced if an effective TE measurement is sought. A straightforward way to ensure that the effects of rebound and shifting are taken into account is to set clear goals and boundaries for the measurement. Effective goal and boundary setting avoids potential errors or omissions due to rebound or shifting. Direct and indirect goals and metrics are needed, so that it is possible to determine what the effects of a TE-improvement strategy have been. For example, plans for Growth and Transportation Efficiency Centers (GTECs) developed in the state of Washington have identified metrics as VMTs and vehicle occupancy rates (WSDOT, 2009). These metrics are intended to gauge improvements in TE as GTEC-strategies are implemented. However, reductions in VMTs and increased vehicle-occupancy rates are indirect goals of the types of land-use improvement strategies being implemented within the GTECs. A better approach would be to include intermediate metrics that are more directly related to the GTEC plan, such as employment and business density within the GTEC. VMT reductions are not a direct effect of a land-use strategy, but changes in land-use are. Setting intermediate metrics for indirect goals of this type will make it possible to isolate the direct effects of the GTEC-efforts from the indirect effects, thereby discerning if rebound effects are counteracting efficiency gains. Establishing the GTECs for municipalities in Washington is a critical step in setting boundaries for measurement of TE. However, sensitivity analyses of the GTEC boundary will be necessary to ensure that TE gains within the GTEC are not being offset by TE losses outside of the boundary (shifting).

CONCLUSIONS AND DISCUSSION

Concerns about the role of transportation in our dependence on foreign oil and in our increasing emissions of GHGs have prompted a growing discussion of ways to improve TE. In the research literature, a growing interest in strategies associated with TE is evident. However, this paper has demonstrated that most of those strategies are simply concepts which are associated with TE, as opposed to more comprehensive measures of TE.

Although a need for additional work is evident, a few comprehensive, assimilative TE measurement tools from the literature were reviewed. Macroeconomic models, such as the one developed by Barker and Rubin (2007), have been used to explore the relationship between TE-improvement policies and overall energy demand. DEA models have been used to analyze and compare the TE of supply-chain systems, using aggregated input/output variables (Cheon, 2008; Sanchez, 2009). A utility-based model pits cost, reliability, and convenience against the geographic reach of three transportation modes - auto, air, and rail. This model is used to plot the relationship between the TE of each mode (as measured by utility) against distance of travel from the city center (Hagler, 2008).

As any TE measurement tool is developed, though, it will become increasingly important to acknowledge, and measure the effects on “rebound” and “shifting” on efficiency gains. The adequate assessment of these effects presents a challenge to any agency attempting to measure TE to assess improvements over time (temporal application), or to compare two or more transportation systems (operational application). Rebound and shifting effects have been observed where measures which appear initially or in a limited context to improve efficiency actually do not yield overall gains. In the case of rebound, it is apparent that efficiency gains are masked by increased demand which results from the passing of the gains onto the consumer through decreased cost. In the case of shifting, the efficiency gains of one system or region are compensated by losses elsewhere. Only one of the three classes of models reviewed acknowledged and measured the effects of rebound on efficiency gains. Better models are needed to adequately assimilate a wide variety of economic, environmental, human, energy, and operational variables on TE, and to assess rebound and shifting effects.

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