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Perspectives on efficiency in transportation

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Abstract

This paper considers the engineer's, economist's, manager's, and planner's perspectives on transportation efficiency respectively. This paper examines the measures used in each perspective and weighs their advantages and disadvantages for various purposes. It illustrates each measure with an example drawn from the case of the Twin Cities ramp metering shut off. The first section summarizes various measures of mobility that are used to assess transportation. This is followed by an exposition of transportation consumer surplus and its limitations. Similar treatment of accessibility and productivity are provided. The conclusions call for consideration of equity in addition to efficiency when evaluating broader effectiveness and for taking the subjective point of view of the traveler rather than the ''objective'' point of view of the omniscient planner/engineer/economist/manager.

Keywords: Performance based programming; Performance measures; Systems evaluation; Measures of effectiveness; Mobility; Utility; Benefit-cost; Productivity; Accessibility; Ramp metering

1. Introduction

The evaluation of transportation systems garners significant attention in the planning, engineering, policy, management, and economics literatures (Kaplan and Norton, 1996; Caltrans, 1998; Pickrell, 1999). Measures of effectiveness (MOE) include assessments of the efficiency of the system, as well as its equity or fairness, its effects on the environment, and the qualitative experience that users enjoy. This paper addresses efficiency measures put forth by different analysts. Each profession approaches the problem differently, with unique concerns and objectives. While each field adopts what it feels are appropriate, none of the current measures corresponds directly with the perceptions of transportation users, the perspective of the *consumer*. As shorthand, we can develop a chart to consider several of those perspectives on efficiency:

Perspective	Profession
Mobility and **S**afety	Engineers
Utility (Consumers' Surplus)	Economists
Productivity	Managers
Accessibility	Planners

The reasons for the different measures are that their uses vary: planning, investment, regulation, design, operations, management, and assessment are among the aims. Where the traveler fits is not immediately clear, as each profession asserts that it is primarily concerned with the public interest.

Engineering textbooks say ''The challenge of the transportation engineering profession is to assist society in selecting the appropriate transportation system consistent with its economic development, resources, and goals, and to construct and manage the system in a safe and efficient manner'' (Garber and Hoel, 1999, p. 13). While including economic criteria, the text proposes multiple criteria for evaluation. In general, engineers focus on maximizing mobility (the speed and capacity of the system) and safety, subject to cost constraints, as the

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other perspectives are out of their control, but tend to concentrate on parts of the network rather than the trip as a whole.

A planning textbook says "Urban planners and scholars have long argued that the ease with which people can reach employment locations, retail and service outlets, and recreational opportunities should be considered in any assessment of the health of a city. They have implied that accessibility should be a central part of any measure of quality of life (see e.g., Chapin, 1974; Wachs and Kumagai, 1973)." (Hanson, 1995, p. 5). Planners looking at the longer term consider the location of places with respect to each other in the accessibility measure, which traveler's consider in real estate decisions.

A transportation economics text discussing project evaluation states "The starting point for measuring costs and benefits is *willingness to pay*: the amount of money each individual would be willing to pay for the change in his or her circumstances. … Therefore willingness to pay for a price reduction is correctly measured by the change in consumers' surplus, which is the area under the demand curve and above a horizontal line indicating the current price." (Small, 1999). Economists measure utility (or consumer's surplus), in the hope of having incorporated traveler's preferences, and try to ensure that benefits exceed costs, but admit that utility cannot be completely measured.

Managers try to keep costs down and maintain the productivity of the system. Novack, Rinehard, and Langley (cited in Coyle et al., 2000, p. 15) conducted a survey of logistics executives. "Changes in logistics productivity do not result in reactions from customers … Productivity improvements in logistics are important to internal customers, however, namely upper management".

In addition to these efficiency aims, the political system is also concerned with fairness and justice, which are very difficult to define, while striving to guarantee that public facilities are adequate or that an overall level of service standard is met (Levinson, 2002). The professions generally take the "objective" viewpoint of the omniscient central planner (who may in fact be an engineer, manager, or economist) rather than the "subjective" perspective of the travel consumer.

These perspectives often have implicit within them a spatial dimension, the area or network elements that will be considered in the analysis. Broadly, we can think of a hierarchy of geographical units. The individual link (road segment) can be aggregated in one of two ways, by area into a subnetwork, or by path (route) into a trip. All links comprise the network, which is a collection of subnetworks. Each trip also uses a set of links between an origin and destination. The spatial aggregation dimension needs to be considered along with the various perspectives, as improving one component (say a link) may do little good for other components (other links, specific trips, or the network as a whole), and may sometimes worsen them.

We also need to distinguish between the normative (what should be) and the positive (what is) when considering efficiency measures. For each measure, we need to define a scale across which values are compared. To say that the speed on a link is 50 km/h tells us nothing about whether that is good or bad, it simply *is*. By comparing the measured speed of 50 km/h to a normative standard (for instance, a speed limit), we can then determine whether we have a speeding problem (the speed limit is 30 km/h), a congestion problem (the speed limit is 110 km/h), or no problem.

Several attributes help define good MOE. While this list is by no means definitive, it may help in selecting MOEs.

(1) Different measures (e.g. transit and auto level of service) should be collectively complete in that one could combine them to attain an overall measure.
(2) Each measure should scale or aggregate well (e.g. it should be possible to combine measures of auto level of service measured on separate links or for separate trips).
(3) Each measure should allow for disaggregation and analysis of components (e.g. it should be possible to take a measure of transit level of service measured for the system and disassemble that measure to obtain measures of components of the system).
(4) The measure should align with user experience and be understood by those users.
(5) The performance indicator must be measurable, or calculable from available (observable) data.
(6) The measure should be predictable, or able to be forecast.
(7) It must be useful in a regulatory or control context (so that the measure can be used to allow or restrict new development to maintain standards, or to help guide operational traffic engineering decision).

This paper considers the engineer's, economist's, manager's, and planner's perspectives on efficiency for transportation respectively. This paper examines the measures used in each perspective and weighs their advantages and disadvantages for various purposes. It then applies each of the measures to the case of the Twin Cities Ramp Meter shutdown, which took place in 2000 (the details of the study can be found in Levinson et al., 2004). While the measures might not align exactly with each profession's current practice, it is hoped that this shorthand will provide insight into the problem of how different measures are, and can be, used. The first section summarizes various measures of mobility that are used to assess transportation. This is followed by an exposition of transportation consumer surplus. Similar treatments of accessibility and productivity are provided. A discussion of the traveler's perspective is then provided. The conclusions call for broadening evaluation beyond efficiency and into equity and for taking the subjective point of view of the traveler rather than the "objective" point of view of the omniscient planner/engineer/economist/manager.

2. Mobility

2.1. Definition

Handy (2002) notes, "The terms 'accessibility' and 'mobility' are often used together in transportation plans but without clear distinction." In brief, mobility measures describe the ease with which elements of the transportation system, or the transportation system as a whole can be used—how the network facilitates movement. However mobility measures do not weight the ease of movement by the number of places that can be reached, which is incorporated in accessibility measures described in a later section.

The *Highway Capacity Manual* (HCM) (TRB, 2000) distinguishes transportation facilities by type; highways are divided into interrupted and uninterrupted facilities. The HCM is a document designed by a committee, as illustrated in its multiplicity of measures for different facility types. For basic freeway segments, density is preferred to speed measures because speed is relatively invariant to traffic flow until volume is very close to capacity. Level of service ranges from A to F, level of service E is the critical density, that is the density at which capacity is reached.

The perspective offered in the *Highway Capacity Manual*, however, only measures mobility on individual network elements, not trips, subnetworks, or the network as a whole. The Texas Transportation Institute (TTI) has developed a methodology to compare congestion between urban areas (Texas Transportation Institute, 2000). For metropolitan areas, TTI estimates travel speed, travel delay, system travel speed, travel rate index, fuel economy, wasted fuel, and congestion cost among other measures. Travel delays are classified into recurring and incident delays.The data used for TTI analysis are obtained from the US DOT's Highway Performance Monitoring System (HPMS), which compiles information on roadway systems maintained by state and local agencies, as well as from local planning, transportation agencies, and state DOTs.

Automobile measures of mobility (or level of service) can be classified by at least two criteria. The first is scale of analysis; for instance intersection approach, total intersection, road segment, or a road network can all be the basis for measurement. The second is kind of measurement—volume or time. Table 1 arrays some measures by this scheme. Other automobile level of service measures include: parking availability and cost, network connectivity, conflict with non-auto system (e.g. pedestrian crossings), hazard rating, service station availability, ride comfort, aesthetics, and traveler information (knowledge of expected delay).

In general, volume is easier to measure, as it requires less tracking than delay, and is easier to accurately predict, as delay depends on more factors (including signal timings and cross-traffic). Similarly, the intersection approach is the most detailed level of analysis, and is how travelers subjectively perceive the intersection. However, from a broader perspective, there is some desire to aggregate the measures (after all, trips occur on multiple segments, and the success of the system depends on more than one component). This suggests that all three levels of detail (network, link, intersection) may need to be assessed.

Commuters do not directly perceive volume-to-capacity ratios and may only have a sense of traffic density. But they do perceive travel time. Delay lends itself more easily to a trip measure than does capacity.

Table 1
Some roadway mobility measures

Scale	Delay measures	Capacity measure
Intersection approach	Stopped delay	Volume to capacity ratio
		Queueing
Intersection	Average stopped delay	Critical lane volume: (CLV)
Road segment	Average delay (Actual time – Freeflow time)	Density
	Average travel speed	Volume to capacity ratio
Road network	Average travel speed	Cordon volume/cordon capacity
	Average percent delay	Screenline volume/screenline capacity
	Average trip time	Average congestion index: the (weighted) average volume to capacity ratio for an area's links
	Shoulder hour index (shoulder hour time/peak hour time)	Average of area intersection: the (weighted) average of CLV
	Percent of trips with delay>X	The percent of links at each LOS

Table 2
Some non-auto system mobility measures

Stage	Time	Volume and capacity
Walk (bike) and walk access and egress to transit	Walk travel time	Sidewalks/roadways (bikeway/roadway)
	Circuity	Connectivity
	Delay	Hazard
	Aesthetic	Bicycle parking
Auto access and egress	Auto access travel time	Parking availability and cost
Waiting	Waiting time (frequency)	Waiting comfort
	Reliability	
Transit in-vehicle	Travel time	Use
	Circuity	Comfort of service
	Travel time/travel time by auto	

This is because delay can be aggregated over an area or trip. A trip-based delay measure would consider both intersections and links implicitly; no distinction would be made as to whether delay was caused by an intersection or a link. A volume-based measure would have difficulty incorporating this. [1]

While transportation engineers most often deal with automobile travel, the mobility and safety of non-auto travel should also be considered. The Bureau of Transportation Statistics (1999) reports that the automobile currently serves some 89.5% of daily trips in the United States. However, large segments of the population cannot drive an automobile for their transportation needs. Foremost are children under the age of 15, which the census estimates at 21.3% of the population. The quality of their transportation depends in large part upon many microscale site planning design issues such as the provision of sidewalks, the location of paths and trails, building setbacks, and neighborhood road design which minimizes vehicular speed. Table 2 lists non-auto mobility measures.

2.2. Application

To compare the various classes of measures, we apply them to the same case, the eight-week shut off of Ramp Meters in 2000. Applying some of the mobility to evaluate ramp meters requires measurements at on-ramps, freeway segments and the system as a whole. Total delay, number of vehicles being delayed, average delay through the whole observation period, and average delay of each time interval are computed for each ramp. The travel time and delay for each freeway segment are measured. They are combined through synchronization into a series of OD matrices containing different mobility measures (travel time, travel delay, speed). The results for two roadways (Trunk Highway 169 northbound between I-494 and I-694, a suburban freeway, and I-94 between downtown Minneapolis and downtown St. Paul) are shown in Table 3.

Table 3
Mobility measures with and without meters

		Travel speed (km/h)	Travel time (s/km)	Travel delay (s/km)
With meters	TH169	62	99	68
	I-94	79	89	42
Without meters	TH169	37	113	82
	I-94	87	75	28

Previous research indicates that ramp meters increase the mobility of freeway networks. On TH-169, with ramp metering, the average travel speed (taking ramp delay into account) of the network increases from 37 to 62 km/h; travel delay per km decreases from 82 to 68 s and the average travel time for one trip decreased from 610 to 330 s. However, on I-94, the network mobility measures decrease slightly as the result of the ramp meter control. The average travel speed (taking ramp delay into account) of the network decreases from 87 km/h (without control) to 79 km/h (with control). Travel delay per mile increases from 27.9 s (without control) to 42.1 s (with control) and the average travel time for one trip increases from 285 s (without control) to 299 s (with control).

3. Utility

3.1. Definition

The economist's perspective on efficiency revolves around the notion of benefit/cost analysis. Benefits to users in public projects can be measured as the sum of the utility accruing to consumers. However, because,

[1] Several measures at the trip, subnetwork, or network level are weighted averages. Different weights can be taken, including vehicle kilometers traveled, vehicle hours traveled, link volumes, trips from a zone, or the number of observations (links, zones).

strictly speaking, utility is not measurable, consumers' surplus is often used. Consumers' surplus is the difference between what individuals would pay and what they actually pay. [2] The transportation economist will argue that the sum of the change in consumers' and producers' surplus is the appropriate measure of benefit to compare before and after a widened road, land development, or other change in policy or infrastructure. An economist would recognize each trip between a specific origin and destination at a given time by a given mode for a given purpose, as a distinct market, with its own demand curve. The consumer's surplus is measured in each market with and without the change, recognizing that the number of trips in that market before the change may be higher or lower than the number of trips after the change. The price is the money and time (combined into a generalized cost) required to consume a trip in a particular market. If more people are traveling at the same price, or the same number at a reduced price, or some combination of the two, this is deemed a benefit. This measure is summed across all markets. For any given change, some markets may experience an increase in benefit, others a decrease, and the total may or may not be positive.

Fig. 1 shows conceptually how consumers' surplus is calculated within a single transportation market. This illustrates two networks. Network 2 is a net improvement on network 1, hence the same number of trips can be accommodated at a lower cost (or more trips for the same cost). The consumers' surplus for network 1 is represented as area *a–b–e* and for network 2 as area *a–b–c–d–e*. The difference, or change in consumers' surplus is the area *b–c–d–e*. In practice, point *a* is unknown, so the change in consumers' surplus between two scenarios or networks is more useful than the absolute value of the consumers' surplus.

The numerous transportation markets are coupled, that is the demand in one affects the supply characteristics of another. Thus, a reduction in cost in one market will increase the demand in that market. That demand will use links shared by other markets, where the supply was not expanded. Moreover an increase in demand in some markets will increase costs and decrease trips in others. A direct benefit accrues to a market where the improved link is used or the improved link is at least a partial substitute for a link that is used. In this framework, with variable demand, many markets that do not receive the benefit directly will receive a net loss of transportation welfare.

The elasticity of demand is generally known near existing price points. In the areas beyond the range of

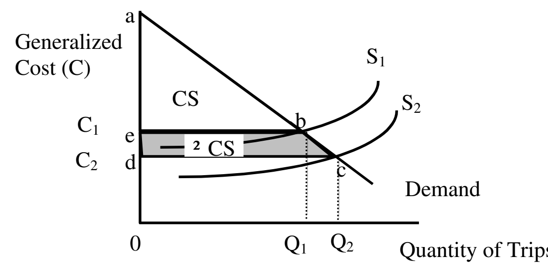

Fig. 1. Consumers' surplus for networks (1) and (2).

our experience, demand is not known well. This is acceptable in the case of the shifts in the supply curve (e.g. adding a new link), when the unknown areas do not enter the measurement. However, with a shift of the demand curve, the whole range of demand must be known to achieve an accurate measurement.

With a consumers' surplus measure, the total change in surplus over all markets needs to be compared with the total costs of the project. In economic analysis, if total benefits exceed total costs, the project is worth doing.

Approximating demand as a straight line function, then the following "rule of 1/2" describes the net user benefit (change in consumers' surplus) (ΔCS) in a single market (Neuberger, 1971):

$$\Delta \mathrm{CS} = 0.5(Q_{\mathrm{off}} + Q_{\mathrm{on}})(\tau_{\mathrm{off}} - \tau_{\mathrm{on}}) \quad (1)$$

where Q_{on}, Q_{off} flows when the ramp meters are on, off respectively. τ_{on}, τ_{off} travel times when the ramp meters are on, off respectively.

3.2. Application

If the travel time when the ramp meters are switched off is greater, then there is a gain of consumer surplus with metering. Using the same afternoon peak period data as was used above in the comparison of mobility, the change in consumers' surplus is measured. On TH-169, the changes in consumers' surplus for each individual segment are summed to get a benefit from metering of 3531 vehicle hours. The loss in consumers' surplus on ramps with metering is found to be 639 vehicle hours. As expected, ramp meters significantly reduce the productivity and consumers' surplus of the ramps. The change in consumers' surplus of the system with ramp metering is overall positive, the ramp meters benefit the freeway segments more than they hurt the ramp segments, so an overall positive change in consumers' surplus of 2893 vehicle hours is recorded. On I-94, the net increase in the consumers' surplus of the whole system (including freeways and ramps) due to metering is 481 vehicle hours.

[2] Similarly, Producers' surplus (or profit) is the difference between the cost of production and the price of sale; but for goods that are unpriced, e.g. most roads, there is no producer's surplus.

4. Productivity [3]

4.1. Definition

In determining whether to build a project, select a policy, implement a system, or provide a service, it is possible, with the help of many assumptions, to estimate the net present value of the future stream of profit or welfare with a cost/benefit analysis. But because of the assumptions required, benefit/cost analysis may not be sufficient to manage a complex system such as a transportation network on a day-to-day basis. There is a desire to monitor the transportation network on multiple dimensions, to understand how well it is performing (and how accurate were previous projections), and to steer future decisions. Metrics might assess how efficiently labor or capital is employed (to determine where future labor or capital should be employed). They might consider market share against competitors, the state of complementary services (for instance, access to transit or parking in the case of a transit system) or the satisfaction of customers and vendors (to gauge future market share and the price and quality of inputs).

Productivity is simply a measure of output divided by input. The larger this ratio, the more productive is the system. The key to measuring productivity is determining the outputs and inputs. Beginning with the inputs, we have, broadly, capital and labor. Labor includes all the human time required to produce a service. So when considering the productivity of transit service, labor inputs comprise the employees of the transit agency, including bus drivers, mechanics, managers, and accountants among others. (And when considering passenger car travel, the driver's time must be included as well.) Capital includes all the buildings and equipment needed to operate the service (buses, garages, offices, computers, etc.). Capital may include land and energy, though those are often separated. While labor may go into each of the capital components, to the agency it is viewed as capital (the labor required to build the bus is considered in the labor productivity of the manufacturer of the bus, but not the operator). Labor productivity (P_L) can be measured by dividing the output measure (O) with hours of labor input (H). Similarly, capital productivity (P_K) can be defined as the output measure divided by the capital (K) in money terms that is required to produce that output. Capital is somewhat trickier than labor in that capital is often a stock, while output and labor are flows. For example, if it costs one million dollars to build a road section with a multi-year life, we cannot measure the productivity of capital as simply annual output divided by that one million dollars. Rather, that stock needs to be converted to a flow, as if the highway department were renting the road. This conversion depends on the interest rate and the life of the facility.

In freight, output is typically measured by ton-km shipped, input would be the hours of labor and machinery employed. In passenger travel, output may be person kilometers traveled. So improvements that increase the number of ton-km or person-km that can be transported with the same resources (in the same period of time) increase productivity. Four basic partial productivity measures for transportation are given in Table 4.

Looking at either the productivity of labor or capital to the exclusion of the other is insufficient. Some investments can improve labor productivity at the expense of capital productivity. Total factor productivity measures can be used to combine labor and capital productivity. These require weights for each measure (and any submeasures which comprise a measure) proportional to the share of that measure in total costs. This issue becomes more complex when examining changes in productivity between time periods, as both inputs and outputs (and thus shares) change.

A good argument can be made that it is not always good to maximize travel, we do not want to increase distance traveled by building circuitous routes for in-

Table 4
Productivity measures

Description	Formula
Productivity of public labor (P_{GL})	$P_{GL} = \frac{\sum_l T_l}{\sum_l H_l}$
Productivity of private labor (P_{PL})	$P_{PL} = \frac{\sum_l T_l}{\sum_l D_l}$
Productivity of public capital (P_{GK})	$P_{GK} = \frac{\sum_l T_l}{\sum_l K_l}$
Productivity of private capital (P_{PK})	$P_{PK} = \frac{\sum_l T_l}{\sum_l V_l}$

Where T = Travel on the system in question (person-km or ton-km), H = Hours of labor by employees of the highway agency (including professional drivers), D = Hours of time by the driver and passengers spent on the network in question (excluding professional drivers), K = Dollars of public capital spent (building and maintaining the infrastructure), V = Dollars of private capital spent (the share of the cost of owning and operating a vehicle, exclusive of taxes to pay for public capital for its use on the network in question), l denotes links in the set of links L under question.

[3] The question of *what is productivity in transportation* has several interpretations. One line of research, not followed here, beginning with research by Aschauer (1989) and continuing through Boarnet (in press) and Nadiri and Theofanis (1996) examines how transportation investment affects the economy at large. These papers tend to treat transportation (or highways) as a black box, and make no distinctions between different kinds of transportation investment. The input is state or national investment in transportation, and output is gross domestic product. While this research provides useful rhetorical tools (transportation investments provide an X% return, compared with Y% for other investments) important for large budget debates, it provides no assistance in actually making management decisions.

TRAMAN 18
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Table 5
Productivity measures with and without meters

		Segment		Ramps		Productivity (km/h)
		VKT	VHT	VKT	VHT	
With meters	TH169	339,822	3341	3994	703	85
	I-94	539,286	5494	3785	264	94
Without meters	TH169	271,388	5214	3815	95	52
	I-94	523,027	5940	3819	95	87

stance. Two effects take place when network distance is shortened. First, there is an immediate reduction of ton-km. But there is also a shortened travel time, which may induce more economic activity, trips, and thus ton-km. This paradox can be obviated by looking at point-to-point distance rather than network distance as the baseline.

Productivity is not of itself a perfect welfare measure, especially since it only addresses the costs of production, not the demand side. However it is an indicator whose changes tend to indicate whether welfare is increasing or decreasing. As emphasized earlier, other gauges may be required to indicate overall welfare. Furthermore, we have only described the productivity of transportation, not the activity system to which all travel belongs.

4.2. Application

Productivity is the ratio of the output of any product to the input that was required to produce that output. For freeway networks, vehicle kilometers traveled (VKT) is the main output and vehicle hours traveled (VHT) is the main input. In this case, a partial productivity factor (P) of a freeway network is equivalent to a measure of network average speed, but is weighted differently than a mobility measure, which would average link speeds:

$$P = \frac{\text{output}}{\text{input}} = \frac{\sum \text{VKT}}{\sum \text{VHT}} = \frac{\sum QL}{\sum Q\tau} \qquad (2)$$

The ratio of VKT and VHT is measured for each freeway segment and ramps separately and then combined to obtain the productivity of the system for both the metering-on and metering-off cases. Ramp metering is considered beneficial if the productivity with its presence is higher.

Table 5 shows productivity, the vehicle kilometers of travel per vehicle hours of travel on freeway segments and ramps. The freeway segments have productivity of 102 km/h with metering and 52 km/h without meters. The net productivity of the ramps themselves is 5.76 km/h with meters and (by assumption) 40 km/h without meters. Combining freeway segments with ramps gives a system productivity measure. The system productivity improves immensely with ramp metering. In fact the percentage increase in system productivity is 64%. For I-94, Table 5, suggests an increase in the productivity of the system by 8.26%. This compares with a drop in speed using the mobility measures.

5. Accessibility

5.1. Definition

Accessibility is the measure of the ease with which other pieces of land and their associated activities can be reached (Hansen, 1959; Black and Conroy, 1977; Pirie, 1981; Morris et al., 1979). Weibull (1980) suggests that accessibility is a measure of an individual's ability to participate in activities in the environment. If a transportation or land use change enables someone to reach activities that are more desirable in less time, then the accessibility (and possibly the value of their land) [4] increases. However, because accessibility increases with activity, areas with high accessibility often have high congestion.

There has long been an interest in the gravity model and in related accessibility measures. In analogy with physics, Reilly (1929) formulated a "law of retail gravitation", and Stewart (1948) formulated early definitions of accessibility. The measure of potential is now called accessibility (Hansen, 1959). Since Hansen's formulation, the distance decay factor has been updated to a more comprehensive function of generalized cost. The function is not necessarily linear—a negative exponential, estimated from models of observed spatial interaction (such as gravity models), is often used. Geographers define accessibility as suggested in Table 6 (Hanson,

[4] Hedonic theory suggests that individuals do not purchase goods, but rather the bundle of attributes composing the good. Someone does not buy a house, but rather the qualities of that house: location (accessibility), size, type of construction, appliances, noise from nearby roads, etc. Every house combines the various attributes slightly differently. Hedonic models are used to pull apart these attributes, and develop demand curves for the various attributes (goods or bads). However, these attributes are interrelated, houses with high accessibility will be more expensive, which will lead to more investment in other attributes, leading to better maintenance and more frequent remodeling.

Table 6
Accessibility measures

Description	Formula
Accessibility (A) in zone i depends on the opportunities (e.g. jobs P) in zone j and the transportation cost τ_{ij} between them	$A_i = \sum_j P_j f(\tau_{ij})$
Job–worker ratio (R) in zone i at radius r (in transportation cost) is the Jobs (P) within radius r divided by Workers (Q) within radius r	$R_i = \frac{\sum_{j=1}^{r} P_j}{\sum_{j=1}^{r} Q_j}$
Density (D) in zone i is the sum of jobs and workers within radius r, divided by the area contained within	$D_i = \frac{\sum_{i=1}^{r} P_i + Q_i}{\pi r^2}$
Difference (Δ) in zone i is the difference between the number of jobs and workers in radius r	$\Delta_i = \sum_{i=1}^{r} P_i - Q_i$
Force (F) between zones i and j is the product of the jobs (P) in zone j and the workers (Q) in zone i and a function of the transportation cost τ_{ij} between them	$F_{ij} = Q_i P_j f(\tau_{ij})$

1986). Some other measures relating jobs and workers (or more generically productions and attractions) are also described in Table 6. Accessibility is illustrated in Fig. 2, where the propensity is the willingness to travel a certain distance (the longer the distance/time, the less willing you are to travel), the job supply is the cumulative number of jobs available (which increases with distance/time over which you are searching), and the actual distribution of trips is a product of those two factors.

If one takes jobs as supply, and workers as demand, there are many ways to inter-relate the two measures. Force (used as an accessibility measure in the early literature), described in Table 6, is analogous to the sum of the area formed by the product of supply and demand. The difference (Δ) between jobs and workers can be viewed as the surplus or deficit in workers at a given travel time away from a point. If for short distances from an individual's house, there is a surplus of jobs, that individual will have a shorter than average commute, while if there is a surplus of houses, there will be a longer than average commute (Levinson, 1998). Taking a simple job–worker ratio (R) over some small subregional geography (Cervero, 1989, 1996) is clearly a misleading indicator (Giuliano and Small, 1993; Levinson, 1998). Nevertheless, it may be useful to compare the relative distributions of jobs and housing without falling into a geography trap. A more sophisticated measure would compute the accessibility to jobs and to workers at a point, and take the ratio of these two accessibility measures. It should be noted that accessibility to housing varies much less than accessibility to jobs. The sum of supply and demand, jobs and workers, can be taken as a net measure of activity in an area, or after dividing by area, as a measure of density.

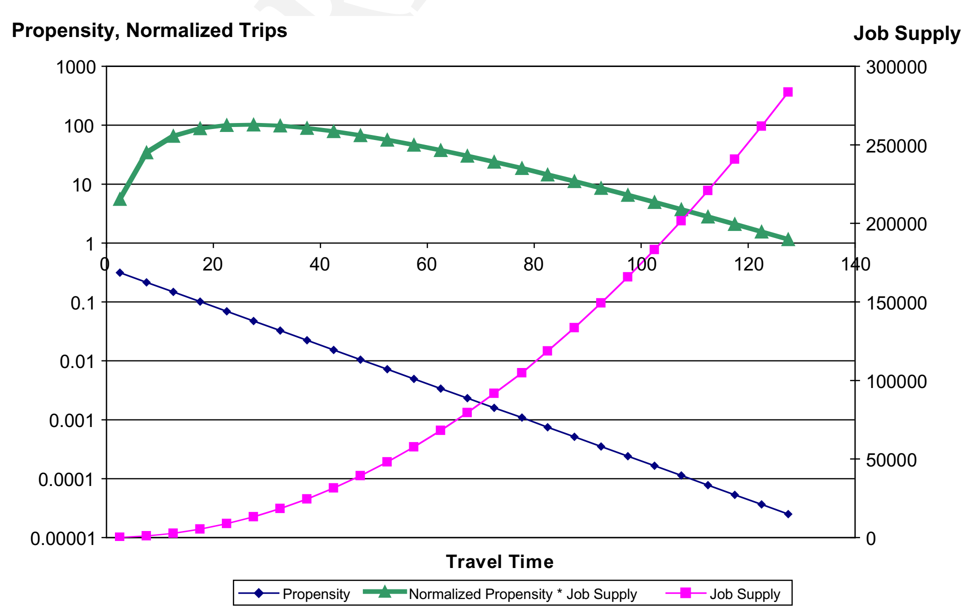

Fig. 2. Accessibility.

Table 7
Accessibility measures with and without meters

Model	TH169			I-94		
	With meters	Without meters	% Change	With meters	Without meters	% Change
$f(\tau_{ij}) = 1/t_{ij}^2$	2.9	2.5	16	12.5	8.5	46
$f(\tau_{ij}) = \mathrm{e}^{-0.00189 t_{ij}}$	58,932	34,502	71	42,977	43,597	−1.4
$f(\tau_{ij}) = \mathrm{e}^{-0.08 t_{ij}}$	93.2	63.772	46	822.5	456.9	80

5.2. Application

Three different functions of travel time are used; these are described in Table 7. Freeway accessibility is computed both with and without ramp metering as in Table 6 (top row), where P_j, the opportunities at off-ramp j, is measured using exit volumes and the travel cost, τ_{ij} is just the travel time between on-ramp i and off-ramp j.

Three different accessibility models were applied to TH169. The first is a classic gravity model, the second a model estimated for freeways in the Twin Cities by the author, and the third from a regional gravity model estimated for Washington DC (Levinson and Kumar, 1995). For all three cases on TH-169 accessibility increases with ramp metering, as shown in Table 7. However, there may be accessibility functions for which this is not the case. The accessibility measures for I-94 are also shown in Table 7. Unlike TH-169, but consistent with our mobility measures, these results are mixed. In one of the three cases, accessibility falls with metering.

6. Travelers: subjectivity and equity

A first criticism concerns the measure of transportation rather than activities as the base for the MOE. A transportation or land use change that enabled a person to reduce the total number of trips made might be seen as a net loss from a narrow transportation productivity or consumers' surplus measure with trips or person-km traveled as the output measure, or a mobility measure that looked at throughput However if the reduction is because of trip chaining, performing the same number of activities with less travel, the individual may be better off. *This argues for a broader measure of utility of the entire activity system rather than simply the demand of the transportation system.* Of course, this also requires entirely new measurement methods.

A second criticism is of the aggregation error involved. Supply and demand curves, and consequently accessibility and consumers' surplus measurements, implicitly assume mass produced identical commodities. If the markets are defined coarsely (large zones, few purposes, few or no time slices), the assumption of homogeneity within markets fails. On the other hand, if each individual trip were its own market, supply and demand curves are no longer measures of quantity of exchange, but rather its probability. While the number of coarse markets was large, the number of potential individual transactions is huge. This clearly makes an accurate measurement of consumers' surplus difficult.

A third criticism is the absence of the consideration of choice and the existence of non-user benefits in the MOE. If transportation is a derived demand, the activities at the end are what count. It can be argued that not only the activities pursued, but also the ones not pursued, should be considered in evaluation.

Further these measures incompletely capture the costs and benefits associated with spillovers and externalities. Transportation change enables/requires reorganization of processes, which provides benefits/costs outside the transportation sector. Particularly in the case of unpriced transportation, it is very difficult to capture these spillover benefits or external costs and internalize them within the transportation sector.

The general focus on systematic efficiency ignores equity effects on individual welfare from a change in the transportation-land use system. While at one level everyone understands that change creates winners and losers, at another, only the aggregate net gain is generally considered. Much cost benefit analysis is based on the Kaldor–Hicks or potential Pareto improvement test. This says that a change is acceptable provided the losers could be compensated from the gains of the winners, whether or not they actually are. But this test may not command social acceptance, particularly from the losers. Thus, economic decisions are devolved into the political and legal arenas, where voices are not necessarily weighted equally. Diffuse winners may not expend energy to defeat concentrated losers, despite an overall "net gain." By the economic calculus, society is worse off. Can this be anticipated and avoided?

It needs to be recognized that winners and losers are created all of the time. The simplest changes to the transportation network create winners and losers, not just due to the taking of land, or the creation of pollution effects, but even mobility reductions from the relatively narrow transportation perspective. It is essential to develop MOE (both of efficiency and equity) that identify these issues before they become political problem. Unfortunately, no single MOE will capture everything. Complexity implies uncertainty, so any one measure will be incomplete. Yet, the alternative of not doing the analysis is also unacceptable. Explicit consideration of equity and the distribution of winners and losers will highlight potential problems before they manifest themselves.

Just as Einstein noted that the point of view of the observer shaped the measurement of time, point of view also affects the perception of time as a measure of transportation level of service. Moving towards trip-based measures will more closely align with how users experience travel. For instance estimating the travel time of individual trips, and looking at the distribution of changes in travel times resulting from changes to the transportation—land use system will allow even systematic and objective measures to get at the same perceptions that are subjectively experienced. However more research is needed into how individuals perceive travel, and how they value or weight components of the travel experience.

7. Conclusions

This paper identified four major classes of efficiency measures: mobility, utility, productivity, and accessibility. Each has strengths and weaknesses, justifying its use, but not its exclusive use, as a gauge of the performance of the transportation system. Like the blind men examining the elephant, there is no single perspective that can be accurately measured and will correctly describe the system. In fact, looking at the Twin Cities Ramp Meter shut down data shows that while sometimes the measures align with each other and all give a clear message (ramp meters were efficient on TH-169), in other cases the results are contradictory (ramp meters may or may not have been efficient on I-94).

Mobility is the traditional measure used by engineers, and has the advantage of ease of measurement. Travel time is a useful measure that aligns with user experience, but users care about trips rather than simply links. There is a reason these measures are used by transportation engineers, the data is easy to relatively easy to collect. It is most appropriate to use mobility when looking at short-run, small-scale system change, especially traffic operational improvements. It can be thought of as the most tactical measure. In general it should track productivity and consumers' surplus, but the results may differ if the two situations being compared are very similar. Mobility measures may also be useful for filtering analysis. Since mobility is easy to measure, ranking sites to study more intensively with e.g., a measured volume/capacity ratio, and then doing a more thorough analysis is a cost-effective approach when the cost of analysis is significant.

Productivity is important to examine when managing the system, and especially for measuring the efficiency of the supply-side, but again it is not experientially based. Productivity are appropriate in a somewhat larger scale than mobility, but are still relatively short-term measures. It may be appropriate to look at small-scale investments that should not have system-wide repercussions. It is tactical, but not as short-term as mobility.

Utility might match travelers the best, if only it could be measured. Consumers' surplus is a useful system measure, but the aggregation of the measure means that it does not match any particular user's experience. Transportation consumers' surplus is appropriate for medium-term evaluation of major investments that have relatively minimal effects on the distribution of land uses. This is inherently a more strategic measure than productivity, but as defined here, ignores the value of opportunities that accessibility aims to measure.

Accessibility provides an overview relationship of transportation, activities, and land uses, but is hard to explain and not easily operationalized into policy. Accessibility is critical to look at the long-term impacts of major investments and the impacts of land use regulatory changes. This is the most strategic measure.

A key difficulty is that subjective perspectives of travelers contrast with the objective views of professionals. There is no single "*subjective perspective of travelers*," as different travelers will by definition have different perceptions. Taking the driver's eye (passenger's eye, pedestrian's eye) point-of-view (looking at trips for instance, or potential destinations) rather than a bird's eye assessment is a start. Defining the specific measures may not be too difficult, (e.g. travel time is one obvious consideration), although weighting those measures requires empirical work (not all time is created equal from the point-of-view of the travelers, a large body of research suggests that waiting time is more onerous than in-vehicle time). But only by considering that subjective perspective as an input can those decisions be implemented in a political environment where everyone has a different viewpoint and set of values.

8. Uncited references

Garber and Lester (1999), Levinson (2000).

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