Measuring Transportation Performance

Now, traditionally, traffic experts have operated with one objective: to move people into and around cities as rapidly and efficiently as possible.... But of course that is no solution.... Cities should be an end, not a means.[1]

by Reid Ewing

We keep seeing references to the need for a "paradigm shift" in land use and transportation planning.[2] If a paradigm shift is called for in planning, it is equally so in the way transportation system performance is measured. In brief, there should be less emphasis on how fast vehicles move and more emphasis on how well peoples' travel needs are met.

The Old Paradigm — Speed

Roadway levels of service (LOS) have long been used in systems planning and traffic operations. Levels of service measure roadway performance on an A to F scale, like a student's report card. LOS A represents free flow, LOS F gridlock. Transportation planners and traffic engineers pursue good "grades" with single-minded determination.

When the architects of growth management began looking for ways to measure the adequacy of public facilities and services, roadway levels of service were both handy and legally defensible. They were embraced without reservation. What had been the planner's and engineer's overriding concern became the policy maker's.[3]

Make no mistake, levels of service, while defined broadly, are really proxies for vehicle operating speed.[4] For urban and suburban arterial, they are a simple function of average travel speed.[5] For other types of roadways, the relationship to speed is less direct but no less germane. Once a roadway's design speed is set, levels of service become a simple function of average travel speed.[6] In planning a new road or road widening, level of service will, understandably, be of prime concern. After all, the purpose of the facility is to move traffic.

Growth management is another matter. How best to utilize existing facilities is as important as what to build anew. Energy conservation, neighborhood protection, downtown revitalization, and other public purposes vie for priority with the desire for free-flowing traffic.

TRANSPORTATION QUARTERLY, Vol. 49, No. 1, Winter 1995 (91-104)

TABLE 1: ARTERIAL LEVEL OF SERVICE—A PROXY FOR SPEED

Arterial Class	*I*	*II*	*III*
Levels of Service	*Average Travel Speed (MPH)*		
A	35	30	25
B	28	24	19
C	22	18	13
D	17	14	9
E	13	10	7
F	13	10	7

Source: Transportation Research Board, *Highway Capacity Manual*, Washington, D.C., 1989, p. 11-4.

One particularly important public purpose, control of urban sprawl, tends to be undermined by the single-minded pursuit of speed. Under uniform level-of-service standards, development is precluded in central areas where roads are already congested. Meanwhile, outlying areas with excess roadway capacity remain developable until they, too, become congested. Hence, speed must be pursued conditionally, only insofar as it does not compromise other purposes of growth management.

New Paradigms

It is easy to call for a paradigm shift in transportation performance measurement. But as every wise guy knows, a paradigm is only four nickels, not worth much in the practical world of growth management. If the old "speed at any cost" paradigm is ill-suited to growth management, what is to replace it?

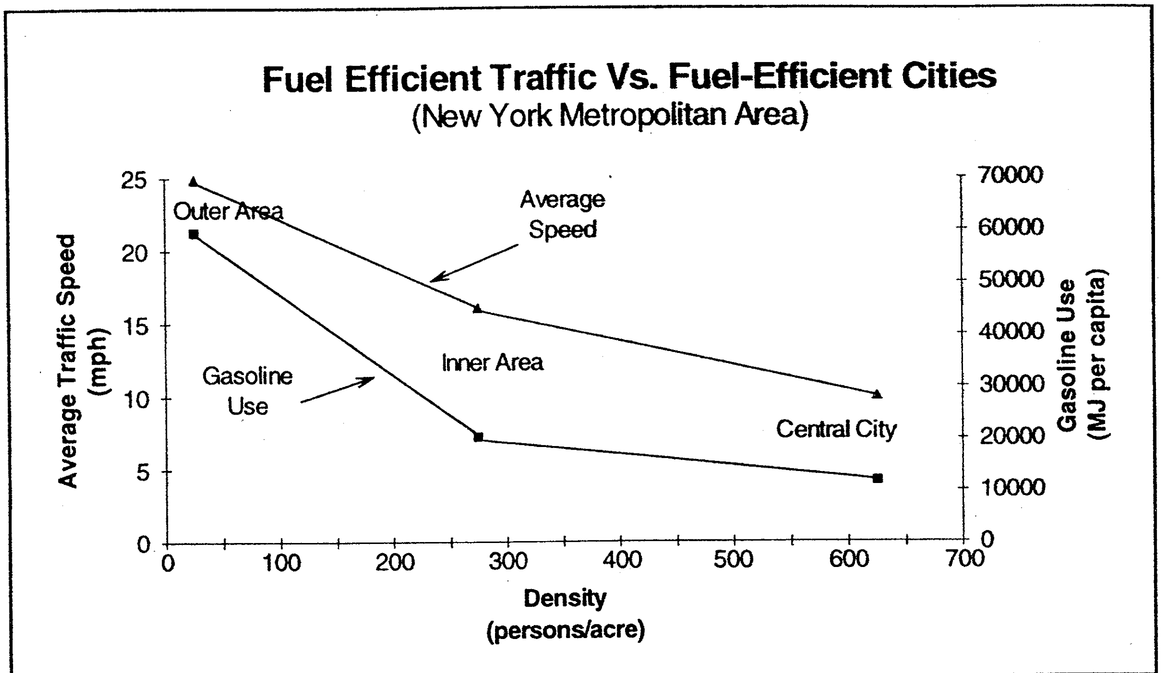
At least four possibilities suggest themselves—mobility, accessibility, livability, and sustainability. Whereas levels of service relate to facilities, "mobility" generally pertains to populations, "accessibility" to land uses, "livability" to communities, and "sustainability" to developments. These terms are used interchangeably on occasion, so let's be clear about the meaning of each.

Mobility refers to the ease with which individuals can move about.[7] A mobile population is one that travels freely because the time and cost of travel are moderate and the travel options are numerous. Vehicle operating speed is a measure of mobility, to be sure, but mobility depends on much, much more (for example, auto ownership, parking availability, transit route density, and sidewalk connectivity).

Accessibility refers to the ease with which desired activities can be reached from any location.[8] The more activities available within a given travel time, the better is the accessibility. Thus, accessibility is a function of both land-use patterns and the transportation system that serves them.

Accessibility is a more encompassing goal than is mobility. "...it is not enough to focus simply on the characteristics of the transport system. It is equally necessary to consider the spatial distribution of opportunities, so that transport policies might be evaluated not only in terms of moving the people to the opportunities but also *moving the opportunities to the people* [emphasis added]."[9]

High levels of mobility bring with them high social costs (at least in auto-dependent America). High levels of accessibility have the opposite effect. In the article "The Transport Energy Trade-Off: Fuel-Efficient Traffic Versus Fuel-Efficient Cities," traffic is shown to be more fuel-efficient in low- than high-density areas; this is due to higher running speeds.[10] However, the resulting fuel savings are more than offset by



Source: Adapted from P.W.G. Newman and J.R. Kenworth, "The Transport Energy Trade-Off: Fuel-Efficient Traffic Versus Fuel-Efficient Cities", *Transportation Research-A*, Vol. 22A, 1988, pp. 163-174.

Figure 1.

longer trips and more motorized travel in the low-density areas. In the trade-off between fuel-efficient traffic (good mobility) and fuel-efficient land use (good accessibility), the latter emerges as more important.

Focusing on transportation, a livable community is one that "puts the automobile in its rightful place as one among many options for travel."[11] There are two sides to this. First, automobile traffic must be calmed, that is reduced in volume and speed. Second, other modes must be enhanced, primarily through changes in land use and facility design. Pedestrians, bicyclists and public transit must be given as much priority within the street environment as are automobiles.[12]

The qualities that make a street "livable" are safety from traffic, peace and quiet, attractive appearance, street life, etc.; ease of movement by car is only one quality valued by residents, and not the most important.[13] A livable street environment is better not only for residents and pedestrians, but perhaps even for motorists (since it makes for a more pleasant driving experience).

The concept of sustainability had its origins in the environmental movement. Sustainable development "meets the needs of the present without compromising the ability of future generations to meet their own needs."[14] It does so by conserving natural resources and protecting the natural environment.

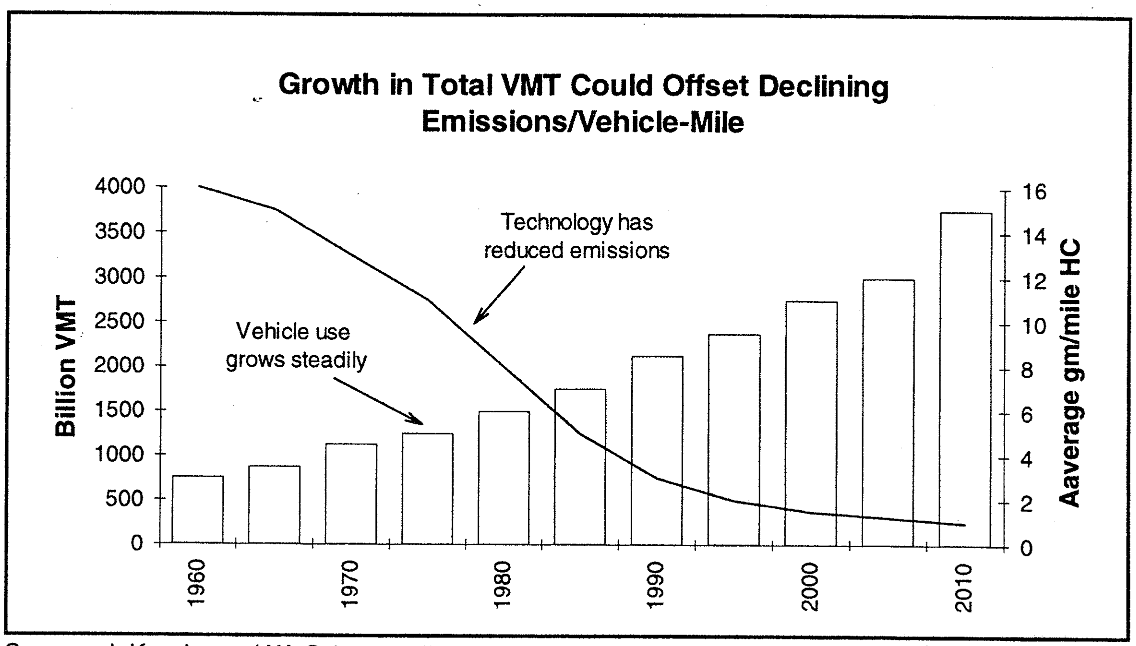
In the transportation sector, the principal threats to sustainability are excessive fossil fuel consumption and the air pollution that results.[15] Both depend on the vehicle miles of travel

(VMT). Both also depend on vehicle trip rates and congestion levels since cold starts, "hot soaks," and low operating speeds add to air pollution and fuel consumption.

Among modes, walking and biking rank highest on the sustainability scale, being non-polluting and non-fossil-fuel consuming. The single-occupant automobile ranks lowest. Transit and ridesharing may rank high or low, depending on how these modes are accessed. "...a reduction in commute VMT may not result in a proportional reduction in mobile source emissions. If carpoolers drive to carpool staging areas in single occupant vehicles or if transit riders drive to park-and-ride lots to take transit, auto trips and therefore cold start emissions are not reduced."[16]

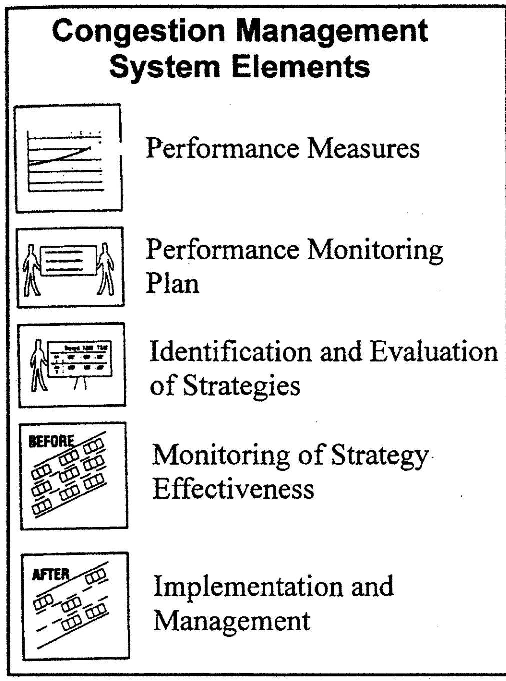
Changes in Federal Laws

A paradigm shift is already underway thanks mostly to changes in federal laws. The federal Clean Air Act Amendments of 1990 require states to develop plans (State Implementation Plans) for attaining national air quality standards in polluted areas. Three performance measures — VMT, vehicle trips, and average travel speeds—play key roles in the plans and related air quality monitoring.[17] VMT, vehicle trips, and average travel speeds are forecasted and tracked, and additional control measures automatically triggered if target levels in the plans are not met. In high ozone and carbon monoxide areas, plans must include transportation control measures (ridersharing programs, high-occupancy vehicle lanes, etc.) sufficient to offset emissions from the growth of VMT and vehicle trips. The federal emissions model, upon which air quality forecasts are based, uses average travel speeds to estimate emission factors (in grams per mile); emission factors are then multiplied by VMT to obtain total emission levels.



Source: J. Kessler and W. Schroeer, "Meeting Mobility and Air Quality Goals: Strategies That Work," *Office of Policy Analysis*, U.S. Environmental Protection Agency, Washington, D.C., 1993.

Figure 2.



Source: JHK & Associates, *Congestion Management for Technical Staff, Three Day Training Course*, Federal Highway Administration, 1994, p. 2-24.

Figure 3.

The federal Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) requires states and metropolitan planning organizations to develop congestion management systems. Such systems must include performance measures and performance monitoring. The federal government has supplied long lists of possible performance measures, ranging from average travel time per trip to number of persons using HOV (high occupancy vehicle) lanes.[18] As to which measures should be employed, the only federal guidance is that the movement of people, not just vehicles, should be measured.[19]

In sum, changes in law and regulation are moving the nation away from vehicle operating speed as the be-all, end-all of transportation planning. Mobility is being viewed, for the first time, in a multimodal context. The aggregate volume of travel is being treated, for the first time, as something to be minimized rather than maximized. Within this context, localities and metropolitan planning organizations have freedom to innovate in their selection of performance measures.

Guidance from National Sources

Several recent articles and reports on performance measurement have been generated by (or have helped generate) changes in state and federal laws.[20] The articles and reports review alternative performance measures and, in some cases, provide general guidance regarding the choice of measures.These sources agree on the following:[21]

- Different levels of analysis require different performance measures. Some measures are well-suited to individual facilities, others to travel corridors, and still others to regional networks.
- Different purposes/uses require different performance measures. One set of measures may be appropriate for design and traffic operations, another for congestion management, a third for growth management.
- The experience of travelers is what counts, not the condition of facilities. Thus, for example, average travel speed on a facility is a better performance measure than is the volume/capacity ratio to which average travel speed relates.
- Mobility must be measured in multimodal terms where modal options exist. This may be accomplished with combined highway-transit measures or separate measures for highway and transit facilities.
- Accessibility must be accounted for at some level of analysis. Accessibility (not mobility) ultimately determines travel time, and travel time (not delay at a single intersection or speed on a single link) ultimately determines impedance to travel.
- The simpler and more understandable performance measures are, the

more useful they will be to decision makers.

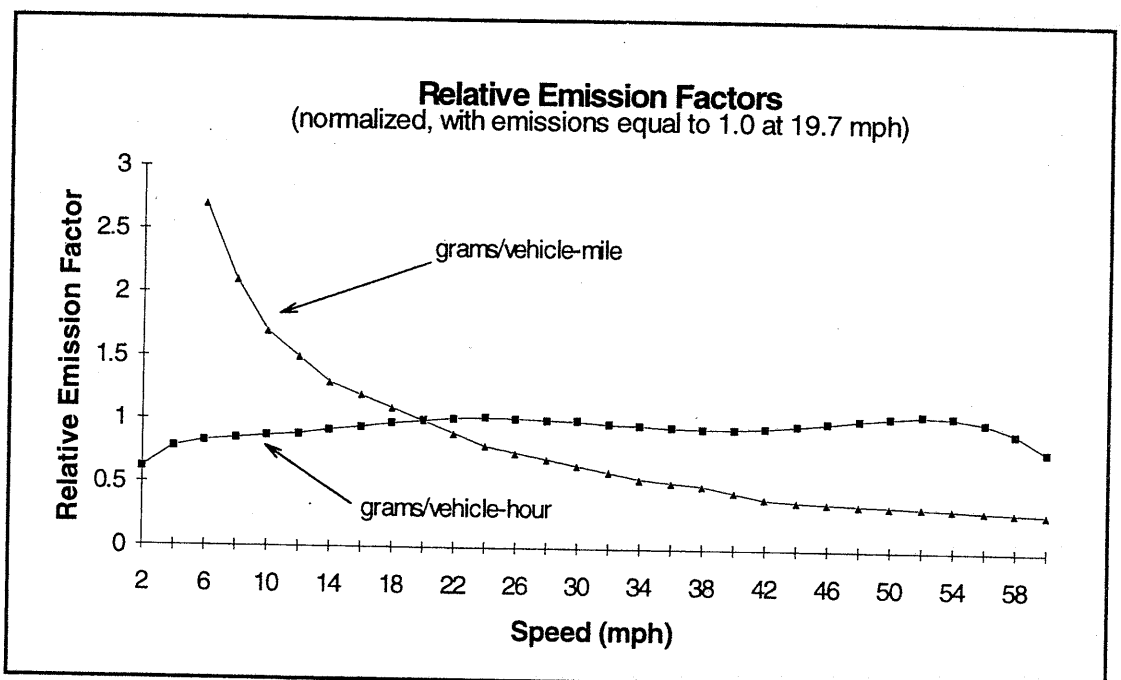
Unified Approach to Performance Measurement

The following makes a conceptual leap from the preceding general guidelines to a set of specific performance measures.

Systemwide Goal. Development of a unified performance measurement system starts with a systemwide goal. Two goals stand out as easily operationalized and consistent with our new travel paradigms.

One worthy goal is to minimize vehicle miles of travel (VMT) or VMT per capita within the region or locality. VMT is related to accessibility, sustainability, and somewhat to livability, as we have defined these terms. VMT was chosen in the *Clean Air Act* as the principal travel measure for air quality planning in high ozone and carbon monoxide areas. VMT has a simple elegance for growth management as well.[22] If development is compact, VMT will be low. If land uses are mixed, VMT will be low. If the road network provides direct connections, VMT will be low. If transit and ridesharing are well utilized, VMT will be low.

Another worthy goal is to minimize vehicle hours of travel (VHT) or VHT per capita within the region or community. VHT has one big advantage over VMT. It accounts for the degree of congestion; all else being equal, the more congested roads are, the more hours of travel will be logged. Mobility, as we have defined



Source: Adapted from L.E. Seitz, "California Methods For Estimating Air Pollutant Emissions From Motor Vehicles," Paper presented at the 82nd APCA/AWMA Annual Meeting, 1989.

Figure 4.

it, is embodied VHT but not in VMT.

In addition, VHT may be a better proxy for accessibility and sustainability than is VMT. In travel modeling, accessibility is usually measured in terms of travel time rather travel distance because travelers' decisions are more affected by time than distance. In air quality modeling, while vehicle emissions can be estimated in terms of either VMT or VHT, the relationship to VHT is simpler and hence more useful for performance measurement. You see, emissions per vehicle mile decline with vehicle operating speed, and therefore a reduction in VMT need not result in reduced emissions; it all depends on how average vehicle operating speeds are affected.[23] By contrast, emissions per vehicle hour are largely independent of speed, and any reduction in VHT should result in reduced emissions.[24] (A similar relationship exists for fuel consumption, the other threat to sustainability.)

Thus, we will adopt a systemwide goal of minimizing VHT, and see where it leads for performance measurement.

Regions and Localities. For regions and localities, several performance measures naturally follow from the formula for VHT:

$$\text{VHT/person} = \frac{\text{average trip frequency x average trip length x (1 - average walk-bike share)}}{\text{average vehicle occupancy x average vehicle operating speed}}$$

All terms on the right-hand side of this equation are performance measures. They satisfy the general guidelines set forth above (that is, they are simple and understandable, multimodal, etc.). Their biggest shortcoming is in the area of data availability.

All could be estimated via household travel surveys. But such surveys are expensive and are conducted only when regional travel models are being updated. Therefore, the best and perhaps only way to estimate VHT on a regular basis is by means of those same regional travel models.

Such models are routinely available to metropolitan planning organizations, regional planning councils, local traffic engineering departments, and consulting firms. They generate estimates of VHT, average trip length, and average vehicle operating speed, as part of their standard output.

Regional travel models can be run for base or future years. They can be run for alternative land use plans in "urban form" studies or for alternative transportation improvements in alternative analyses. They can be run with and without proposed developments to assess the impacts of developments on regional VHT, average trip length, and average vehicle operating speed. Regional travel models are being used already in some areas to assess the impacts of large-scale developments. The difference here is that the bottom-line would be projected regional VHT, not projected levels of service on individual roadways.

Two limitations of these models must be acknowledged.[25] First, their estimates and forecasts are approximate, and particularly so for individual facilities or small subareas; results are more reliable when aggregated across many facilities to arrive at areawide totals. Second, these models are not sensitive to "soft" measures that may affect two terms in the VHT equation —average vehicle occupancy and average walk-bike share. They cannot adequately represent travel demand management (TDM) programs, bicycle-pedestrian facility improvements, and micro mixing of land uses. We would only note that regional travel models are constantly being upgraded (with several state and national projects in progress at this time).[26]

Travel Corridors and Activity Centers. For travel corridors and activity centers, the most relevant terms in the VHT equation are average vehicle operating speed, average vehicle occupancy, and average walk-bike share. Average vehicle occupancy is particularly relevant to freeway corridors where exclusive high-occupancy vehicle lanes and congested conditions make ridesharing attractive. Average walk-bike share is particularly relevant to metropolitan activity centers where high densities, mixed uses, and good pedestrian facilities make walking attractive.

Average vehicle operating speed is relevant everywhere. In the absence of standard methodology, progressive localities throughout the nation have devised their own areawide level-of-service measures.[27] Most have made average volume/ capacity ratios the basis for areawide levels of service. Traffic volumes are summed over several facilities, capacities summed over the same facilities, and the former divided by the latter to arrive at an average volume/capacity ratio. This approach has been applied to intersections in subareas of Bellevue, Washington, and San Jose, California; to roadway segments in subareas of King County, Washington, and Montgomery County, Maryland; to parallel roads in travel corridors of Orange County, Florida; and to roads crossing "screenlines" in Pierce County, Washington.[28]

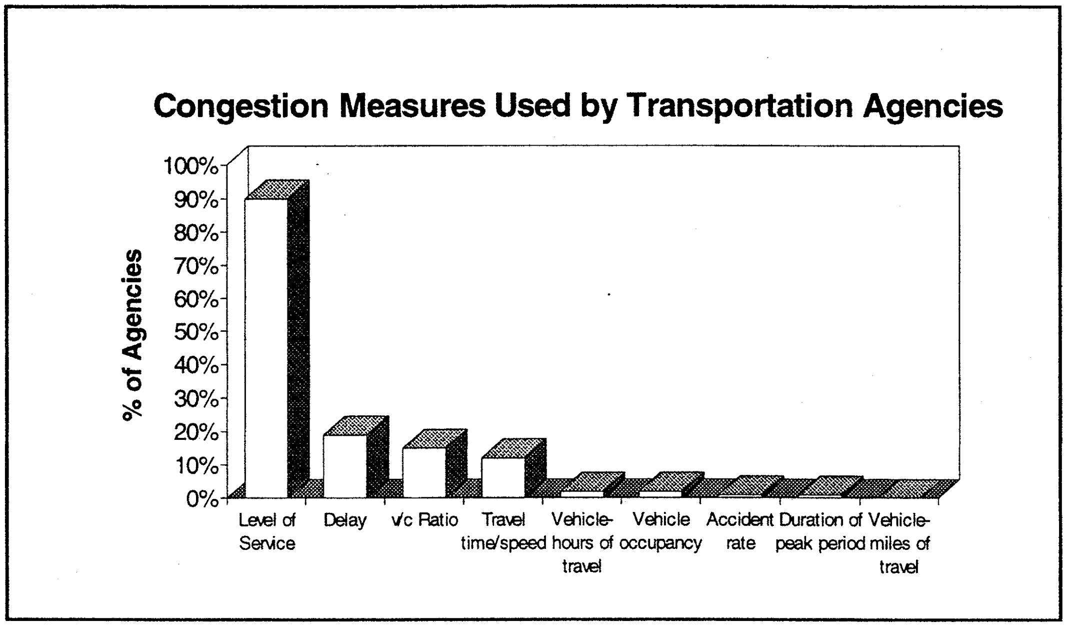
A potentially better basis for areawide level of service is average travel speed. It is a more direct measure of performance than is the volume/ capacity ratio, and is more consistent with the philosophy of the 1985 *Highway Capacity Manual* (which abandoned volume/capacity ratios in favor of direct measures). It is a small step conceptually from averaging travel speeds for roadway segments along an arterial (accepted practice since the *Highway Capacity Manual* was updated in 1985) to averaging travel speeds for parallel roads within a travel corridor or for interconnected roads within an activity center (not accepted as yet but reasonable in the context of growth or congestion management).

With areawide averaging, local authorities will have ample incentive to fix localized traffic problems since travel speeds fall precipitously as capacities are approached on individual segments. Yet, they will not be hamstrung in their use of funds, compelled to bring each and every roadway segment up to some minimum level of service when systemwide investments would be more cost-effective.

Individual Facilities. For individual roadways, the only relevant term in the VHT equation is average vehicle operating speed, or its alias, roadway level of service. There is some interest nationally in switching to delay-based measures of performance for individual roadways. Whatever the theoretical advantages of delay, roadway levels of service have one huge practical advantage—familiarity. Nationally, about 90% of transportation agencies utilize roadway level of service as a congestion measure; no other measure is accepted anywhere near as universally.[29] Roadway levels of service are familiar to all local governments in growth management states.

Moreover, roadway level-of-service standards are written into literally hundreds of adequate public facilities ordinances and several state statutes.[30] Hence any changeover to another performance measure would be hard to effect and partial at best.

Variable Service Standards. If average vehicle operating speed, or level of service, is to remain the basis for judging individual roadway performance, the standard to which it is compared must be a variable one that permits more congestion in central areas. Otherwise, level-of-service standards will inadver-



Source: Adapted from Texas Transportation Institute, *Quantifying Congestion - Interim Report*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 1992, p.55.

Figure 5.

tently drive development to outlying areas where excess capacity exists.

One objective basis for variable service standards is the relative accessibility of an area to trip attractions throughout the region. Better accessibility translates into shorter trips and less total time spent in vehicular travel.[31] The urban core, dense travel corridors, and compact suburban centers may be more congested than outlying areas and still provide better accessibility to trip attractions. Any lack of mobility (in terms of lower vehicle operating speeds) is more than offset by shorter trips.

Variable service standards could be set in one of two ways. Regional travel models or travel surveys could be used to estimate average trip lengths for subareas of a region or locality, and lower level-of-service standards established in subareas generating shorter trips. Alternatively, regional travel models could be used to estimate so-called accessibility indices for subareas, and lower standards established in areas with higher accessibility indices. Accessibility indices reflect the distribution of jobs and other trip attractions moving outward from zones in which trips are produced, with nearby attractions weighted more heavily than distant ones.[32]

Examples. While differing in details, some performance measurement systems in place today are similar in spirit to our idealized system. Orlando uses an areawide level-of-service measure to judge roadway performance in the downtown area. Specifically, the percentage of total lane miles operating at or above a certain service standard is monitored and judged against a goal of 85% at or above. While not as useful as average travel speed, a "% of lane miles" measure at least allows some localized congestion as long as the network as a whole is

Transportation Performance Standards (Orlando's Metropolitan Activity Centers)		
	2000	2010
Transit Mode Split (Work Trips)	4%	7%
Nonautomotive Mode Split (Internal Trips)	15%	25%
Average Vehicle Occupancy (All Peak-Hour Trips)	1.5	No Change

Source: Planning & Development Department, *Traffic Circulation Element*, City of Orlando, FL, 1991, p. TC-20; and Planning & Development Department, *Mass Transit Element*, City of Orlando, FL, 1991, p. MT-4.

Figure 6.

performing adequately.

In addition, Orlando designates activity centers and travel corridors within which performance is to be measured in terms of average vehicle occupancies and/or mode shares, as well as roadway levels of service. In order to achieve vehicle occupancy and mode share standards, minimum densities/intensities and land use mixes have been established for centers and corridors; transit service frequencies are being increased to, through, and within centers; and special taxes are being levied to fund pedestrian facilities and internal shuttle services.

Another example comes to us from the opposite coast. In Tacoma, Washington, transportation performance is measured for groups of facilities, rather than on a facility-by-facility basis. Within specified corridors, 85% of the arterial lane miles must operate above LOS E. Congestion is accepted on the remaining lane miles in an effort to promote HOV use (transit and carpools receiving priority treatment in these corridors). Separate performance measures and standards are applied to transit facilities.

VMT plays a role in Tacoma's transportation planning. Employers are required to reduce employee VMT by progressively increasing percentages over time, achieving a 35% reduction by 1999. Our idealized performance measurement system differs, of course, in that VHT is the bottom line rather than VMT, and VHT is measured for all travel rather than work-related travel to specific sites. But Tacoma's rationale for a VMT standard is identical to our own. Even where roadway levels of service are adequate, vehicular travel is still something to be managed and minimized in the interest air quality, energy conservation, and general social welfare.

Last Word

The land use-transportation system is universally acknowledged to be a "system" of interdependent elements (even if it is seldom planned or managed as such). This has implications for the choice of transportation performance measures. Ideally, measures will reflect the efficiency of both land use patterns and transportation networks; they will acknowledge the multimodal nature of the system; and they will treat the links and nodes as part of a system. We have made an attempt, albeit a preliminary one, to devise a unified set of performance measures that does all of the above.

Endnotes

1. K. Sale, *Human Scale*, Coward, McCann & Geoghegan, New York, 1980, p. 256.

2. D. Brand, "Research Needs for Analyzing the Impacts of Transportation Options on Urban Form and the Environment," In *Transportation, Urban Form, and the Environment*, Special Report 231, Transportation Research Board, Washington, D.C., 1991, pp. 101-116; A. Downs, *The Need For a New Vision for the Development of Large U.S. Metropolitan Areas*, Salomon Brothers, Bond Market Research, New York, 1989; and J. Woodhull, "How Alternative Forms of Development Can Reduce Traffic Congestion," In B. Walter, L. Arkin, and R. Crenshaw (eds.), *Sustainable Cities - Concepts and Strategies for Eco-City Development*, EHM, Los Angeles, 1992, pp. 168-177.

3. R. Ewing, "Transportation Service Standards - As If People Matter," *Transportation Research Record 1400*, 1993, pp. 10-17.

4. Quoting the *Highway Capacity Manual*: "The concept of *level of service* is defined as a qualitative measure describing operational conditions within a traffic stream, and their perception by motorists and/or passengers. A level-of-service definition generally describes these conditions in terms of such factors as speed and travel time, freedom to maneuver, traffic interruptions, comfort and convenience, and safety." Transportation Research Board, *Highway Capacity Manual*, Special Report 209, Washington, D.C., 1992, p. 1-3.

5. Transportation Research Board, op. cit., Table 11-1.

6. Transportation Research Board, op. cit., Tables 3-1, 7-1, and 8-1.

7. The term "mobility" is being used here the same sense as in A. Altshuler, J.P. Womak, and J.R. Pucher, *The Urban Transportation System - Politics and Policy Innovation*, MIT Press, Cambridge, MA, 1979, pp. 252-274; T.J. Lomax, *Relative Mobility in Texas Cities, 1975 to 1985*, Texas Transportation Institute, College Station, TX, 1986; P.M. Jones, "Mobility and the Individual in Western Industrial Society," In P. Nijkamp and S. Reichman (eds.), *Transportation Planning in a Changing World*, Gower Publishing Co., Brookfield, Vermont, 1987, pp. 29-47; and A.T. Reno, "Personal Mobility in the United States," In *Look Ahead - Year 2000*, Special Report 220, Transportation Research Board, Washington, D.C., 1988, pp. 369-393.

8. The term "accessibility" is being used here the same sense as in W.G. Hansen, "How Accessibility Shapes Land Use," *Journal of the American Institute of Planners*, Vol. 25, 1959, pp. 73-76; D.R. Ingram, "The Concept of Accessibility: A Search for an Operational Form," *Regional Studies*, Vol. 5, 1971, pp. 101-107; W.A. Muraco, "Intraurban Accessibility," *Economic Geography*, Vol. 48, 1972, pp. 388-405; J.G. Koenig, "Indicators of Urban Accessibility: Theory and Application," *Transportation*, Vol. 9, 1980, pp. 145-172; A.J. Richardson and W. Young, "A Measure of Linked-Trip Accessibility," *Transportation Planning and Technology*, Vol. 7, 1982, pp. 73-82; and S.L. Handy, "Regional Versus Local Accessibility: Implications for Non-work Travel," *Transportation Research Record 1400*, 1993, pp. 58-66.

9. M.Q. Dalvi, "Behavioral Modeling, Accessibility, Mobility and Need: Concepts and Measurement," In D.A. Hensher and P.R. Stopher (eds.) *Behavioral Travel Modelling*. Croom Helm, London, 1979, pp. 639-653. Also making the distinction between mobility and accessibility are G.V. Wickstrom, "Defining Balanced Transportation - A Question of Opportunity," *Traffic Quarterly*, Vol. 25, 1971, pp. 337-348; W. Owen, "Transport, Energy, and Community Design," *Futures*, April 1976, pp. 94-103; M. Wachs and J.G. Koenig, "Behavioral Modelling, Accessibility, Mobility and Travel Need," In D.A. Hensher and P.R. Stopher (eds.), *Behavioral Travel Modelling*, Croom Helm, London, 1979, pp. 698-710; J.M. Morris, P.L. Dumble, and M.R. Wigan, "Accessibility Indicators for Transport Planning," *Transportation Research A*, Vol. 13A, 1979, pp. 91-109; and S. Hanson, "Dimensions of the Urban Transportation Problem," *The Geography of Urban Transportation*, Guilford Press, New York, 1986, pp. 3-23.

10. P.W.G. Newman and J.R. Kenworthy, "The Transport Energy Trade-Off: Fuel-Efficient Traffic Versus Fuel-Efficient Cities," *Transportation Research A*, Vol. 22A, 1988, pp. 163-174.

11. M.D. Lowe, *Alternatives to the Automobile: Transport for Livable Cities*, Worldwatch Institute, Washington, D.C., 1990, p. 5.

12. H. Topp, "New Concepts in Traffic Planning," In S.H. Crowhurst-Lennard and H.L. Lennard (eds.) *Livable Cities - People and Places: Social and Design Principles for the Future of the City*, Center for Urban Well-Being, New York, 1987, pp. 98-102; and D. Garbrecht, "Walkability - A Prerequisite for Livable Cities," In S.H. Crowhurst-Lennard and H.L. Lennard (eds.), *Livable Cities - People and Places: Social and Design Principles for the Future of the City*, Center for Urban Well-Being, New York, 1987, pp. 109-113.

13. D. Appleyard, *Livable Streets*, University of California Press, Berkeley, 1981, pp. 41-60.

14. World Commission on Environment and Development, *Our Common Future*, Oxford University Press, New York, 1987, p. 8.

15. 15 P. Calthorpe and H. Richmond, "Sustainable Growth: Land Use and Transportation Planning," 1000 Friends of Oregon, Portland, OR, undated; F.A. Reid, "Real Possibilities in the Transportation Myths," In S. Van der Ryn and P. Calthorpe (eds.), *Sustainable Communities - A New Design Synthesis for Cities, Suburbs, and Towns*, Sierra Club Books, San Francisco, 1991; H. Barton, "City Transport: Strategies for Sustainability," In M.J. Breheny (ed.), *Sustainable Development and Urban Form*, Pion Limited, London, 1992, pp. 197-216; P.M.W. Elsenaar and J.A. Fanoy, "Urban Transport and Sustainable Development in the Netherlands," *ITE Journal*, Vol. 63, August 1993, pp. 9-13; and Transportation Strategic Planning and Analysis Office, *Sustainable Transportation: Developing a Framework for Policy Innovation - December 14, 1993 - Summary of Proceedings*, John A. Volpe National Transportation Systems Center, Cambridge, MA, 1994.

16. P. DeCorla-Souza and R. Schoeneberg, "The Transportation - Air Quality Connection: Perceptions and Realities," *ITE 1992 Compendium of Technical Papers*, Institute of Transportation Engineers, Washington, D.C., 1992, pp. 157-162.

17. G. Hawthorn, "Transportation Provisions in the Clean Air Act Amendments of 1990," *ITE Journal*, Vol. 61, April 1991, pp. 17-24; Federal Highway Administration (FHWA), *A Summary - Transportation Programs and Provisions of the Clean Air Act Amendments of 1990*, Washington, D.C., 1992; G. Hawthorne and M.D. Meyer, *Action Guide for the 1990 Clean Air Act Transportation Provisions*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 1992; U.S. Environmental Protection Agency (EPA), *1992 Transportation & Air Quality Planning Guidelines*, Office of Mobile Sources, Ann Arbor, MI, 1992, pp. 15-20, 33-37; and U.S. Environmental Protection Agency (EPA), *VMT Forecasting and Tracking Guidance*, Office of Mobile sources, Ann Arbor, MI, 1992.

18. Federal Highway Administration (FHWA), "Management and Monitoring Systems; Interim Final Rule," *Federal Register*, Vol. 58, December 1, 1993, p. 63464.

19. The following language has been interpreted as calling for multimodal performance measures: "Parameters shall...permit the evaluation of the effectiveness of congestion reduction and mobility enhancement strategies for the *movement of people* and goods [emphasis added]." Section 500.507, 23 Code of Federal Regulations.

20. Ewing, op. cit., 1993; R. Ewing, *Roadway Level-of-Service Determination*, Florida Institute of Government, Florida State University, Tallahassee, 1991; R. Ewing, "Roadway Levels of Service in an Era of Growth Management," *Transportation Research Record 1364*, 1992, pp. 63-70; Texas Transportation Institute, *Quantifying Congestion - Interim Report*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 1992; Center for Urban Transportation Research, *The Role of Level of Service Standards in Florida's Growth Management Goals*, University of South Florida, Tampa, 1993; JHK & Associates, *Issues, Options, and Examples - Level of Service Standards/Concurrency Management Systems - Final Report*, Puget Sound Regional Council, Seattle, WA, 1993; JHK & Associates, *Multi-Modal Transportation Level of Service Policy and Mode-Split Forecasting Tool - Final Report*, Thurston Regional Planning Council, Olympia, WA, 1993, pp. 1-21 through 1-27; J.P. Savage, E.R. Stollof, and C.W. Wolf, "A Survey of Transportation Service Level Standards," *ITE Journal*, Vol. 63, June 1993, pp. 21-25; Cambridge Systematics, "Task B -- Initial Performance Measures," In *Metropolitan Planning Technical Report*, Report No. 2, Federal Highway Administration, Washington, D.C., 1994; L.D. Frank and C.J. Stone, "Applying GMA Concurrency

Requirements to State Highways and Ferries," Office of Urban Mobility, Washington State Department of Transportation, Seattle, WA, 1994; JHK & Associates, "Key Element 3: CMS Performance Measures," *Congestion Management for Technical Staff - Three Day Training Course*, Federal Highway Administration, Washington, D.C., 1994; R.H. Pratt and T.J. Lomax, "Performance Measures for Multimodal Transportation Systems," Paper presented at the 73rd Annual Meeting, Transportation Research Board, Washington, D.C., 1994; and Texas Transportation Institute, *Methods to Quantify Congestion*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 1994.

21. The following discussion draws principally on four sources: Cambridge Systematics, op. cit; Ewing, op. cit., 1993; JHK & Associates, op. cit.; and Texas Transportation Institute, op. cit., 1994.

22. M.R. Birdsall, "Vehicle-Miles-of-Travel - Its Use as a Primary Measurement Tool for Traffic Impact Mitigation and Growth Management," Unpublished paper available from author, Michael R. Birdsall & Associates, Issaquah, WA, 1993.

23. According to the U.S. Environment Protection Agency (EPA), hydrocarbon and carbon monoxide emissions per vehicle-mile decline with increasing average vehicle speed up to about 55 mph. Nitrogen oxide emissions per vehicle-mile follow a different curve, declining with average vehicle speed up to about 20 mph and then rising again.

24. To a first approximation, running emissions depend on how long an engine is running, not on how far it goes. Citing the extreme case, a vehicle idling at a stop light or stuck in gridlock adds to total emissions and total vehicle hours but not to total vehicle miles. Thus, in a stop-and-go traffic environment, emissions will track more closely with VHT than VMT. In fairness, it should be noted that the appropriate basis for air quality modeling -- whether VMT, VHT, or something more sophisticated that reflects the different modes of vehicle operation -- is being debated within EPA and the air quality community. The federal MOBILE model reports emission rates on a grams/mile basis, at least for now, while the California EMFAC model reports them on a grams/hour basis. See L.E. Seitz, "California Methods for Estimating Air Pollutant Emissions from Motor Vehicles," In *Proceedings of the 82nd APCA/AWMA Annual Meeting*, Air and Waste Management Association, 1989; JHK & Associates, "Emission Inventory Needs," *Travel Forecasting Guidelines*, California Department of Transportation, Sacramento, 1992, pp. 77-93; Office of Mobile Sources, *Highway Vehicle Emission Estimates*, U.S. Environmental Protection Agency, Ann Arbor, MI, 1992, p. 17; and C.T. Ripberger et al., "Feasibility of Using Bag II Average Emissions to Represent All Closed-Loop Emissions in a Modal Model," In *Proceedings of the Fourth CRC-APRAC On-Road Vehicle Emissions Workshop*, Coordinating Research Council, Inc., Atlanta, GA, 1994, pp. 5-73 through 5-87.

25. State-of-the-practice in regional travel modeling relies on a structure developed decades ago, and largely unchanged for the past 15 years. Models were adequate for the purpose originally intended -- the sizing of capital facilities (especially highways). But they fall sort of what is required by the Clean Air Act, ISTEA, and Florida's 1993 growth management act. For a critique of conventional models (given new demands), see G. Harvey and E. Deakin, *A Manual of Regional Transportation Modeling Practice for Air Quality Analysis*, National Association of Regional Councils, Washington, D.C., 1993, pp. 3-1 through 3-7.

26. The Florida Department of Transportation has several ongoing projects aimed at enhancing and modernizing the Florida Standard Urban Transportation Model Structure. Also see Cambridge Systematics, *Model Modifications - Volume 4*, 1000 Friends of Oregon, Portland, 1992; Texas Transportation Institute, *Travel Model Improvement Program*, College Station, TX, undated; and B.D. Spear, *New Approaches to Travel Forecasting Models - A Synthesis of Four Research Proposals*, Technology Sharing Program, U.S. Department of Transportation, Washington, D.C., 1994.

27. Center for Urban Transportation Research, op. cit.; Ewing, op. cit., 1992; Ewing, op. cit., 1993; Frank and Stone, op. cit.; and Savage et al., op. cit.

28. Department of City Planning/Department of Public Works, *North San Jose Area Development Policy*, City of San Jose, CA, 1988, pp. 4-7; Orange County Planning Department, *Comprehensive Policy Plan - 1990-2010 - Traffic Circulation Element*, Orlando, FL, 1992, pp. 163-166; Planning and Transportation Commission, "Recommended Transportation Policy Framework," City of Bellevue, WA, 1992; Pierce County Public Works Department, *Service Standards for Arterial Roads*, Pierce County, WA, 1993, pp. 4-6; King County Parks, Planning and Resources Department, *King County Comprehensive Plan*, Seattle, WA, 1994, pp. 110-112;

and Montgomery County Planning Board, *Recommendations for Amending the Methodology for Determining the Adequacy of Transportation Facilities*, Silver Spring, MD, 1994. Also see A.S. Brick-Turin, "Areawide Capacity Analysis," *ITE 1993 Compendium of Technical Papers*, Institute of Transportation Engineers, Washington, D.C., 1993, pp. 473-477.

29. Texas Transportation Institute, op. cit., 1992, p. 55.

30. Ewing, op. cit., 1991; Frank and Stone, op. cit.; Savage et al., op. cit.; ITE Technical Council Committee 6Y-36, "Transportation Elements of Environmental Impact Assessments and Reports," *ITE Journal*, Vol. 58, 1988, pp. 69-75; G. Walters and J.B. Peers, "The Service Level Ordinance as a Growth Management Tool," *ITE 1988 Compendium of Technical Papers*, Institute of Transportation Engineers, Washington, D.C., 1988, pp. 6-11; R.G. Dowling, "Controlling Growth with Level-of-Service Policies," *Transportation Research Record 1237*, 1989, pp. 39-45; and W.E. Baumgaertner and J.W. Guckert, "The Evolution of Adequate Public Facilities Ordinances and Their Effectiveness as Growth Management Tools in Maryland," *ITE 1991 Compendium of Technical Papers*, Institute of Transportation Engineers, Washington, D.C., 1991, pp. 52-58.

31. The relationship of accessibility to trip length and VHT is documented in R. Ewing, "Beyond Density, Mode Choice, and Single-Purpose Trips," Paper submitted to the Transportation Research Board for presentation at the 74th Annual Meeting, January 1995. Also see Handy, op. cit.; S. Hanson, "The Determinants of Daily Travel-Activity Patterns: Relative Location and Sociodemographic Factors," *Urban Geography*, Vol. 3, 1982, pp. 179-202; S. Hanson and M. Schwab, "Accessibility and Intraurban Travel," *Environment and Planning A*, Vol. 19, 1987, pp. 735-748; and P.A. Williams, "A Recursive Model of Intraurban Trip-Making," *Environment and Planning A*, 1988, Vol. 20, pp. 535-546.

32. An accessibility index is the denominator of the gravity model, used in the standard "4-step" regional travel modeling process to distribute trips among traffic analysis zones. The higher the index, the more accessible are trip attractions collectively to a given zone.

Reid Ewing has a diversified background in urban and transportation planning, public policy analysis and politics. He is currently at the Joint Center for Environmental and Urban Problems, Florida Atlantic University/Florida International University, where he works in the areas of growth management, community development and urban design. He is the author of Florida's Mobility Handbook and related technical guides, which signal a shift away from road building as the overriding response to traffic congestion in Florida. He holds master degrees in Engineering and City Planning from Harvard University and a Ph.D in Transportation Systems and Urban Planning from the Massachusetts Institute of Technology.