DEVELOPMENT AND SENSITIVITY TESTING OF ALTERNATIVE MOBILITY METRICS

Literature Review

SPR 716

DEVELOPMENT AND SENSITIVITY TESTING OF ALTERNATIVE MOBILITY STANDARDS

Literature Review

SPR 716

by

James G. Strathman
John P. Gliebe
Kathryn McGovern
David Ruelas

Center for Urban Studies
Portland State University
P.O. Box 751
Portland, OR 97207

for

Oregon Department of Transportation
Research Unit
200 Hawthorne Ave. SE, Suite B-240
Salem OR 97301-5192

and

Federal Highway Administration
400 Seventh Street, SW
Washington, DC 20590-0003

December 2010

Technical Report Documentation Page

1. Report No. Interim	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle		5. Report Date December 2010 6. Performing Organization Code
7. Author(s) James G. Strathman, John P. Gliebe, Kathryn McGovern, David Ruelas		8. Performing Organization Report No.
9. Performing Organization Name and Address Center for Urban Studies Portland State University P.O. Box 751 Portland, OR 97207		10. Work Unit No. (TRAIS) 11. Contract or Grant No. SPR 716
12. Sponsoring Agency Name and Address Oregon Department of Transportation Research Setion and Federal Highway Administration 200 Hawthorne Ave. SE, Suite B-240 400 Seventh Street, SW Salem, OR 97301-5192 Washington, DC 20590-0003		13. Type of Report and Period Covered Interim Report 14. Sponsoring Agency Code
15. Supplementary Notes		
16. Abstract		
17. Key Words	18. Distribution Statement Copies available from NTIS, and online at http://www.oregon.gov/ODOT/TD/TP_RES/	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 47 / 22. Price

Technical Report Form DOT F 1700.7 (8-72) Reproduction of completed page authorized Printed on recycled paper

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

DISCLAIMER

This document is disseminated under the sponsorship of the Oregon Department of Transportation and the United States Department of Transportation in the interest of information exchange. The State of Oregon and the United States Government assume no liability of its contents or use thereof.

The contents of this report reflect the view of the authors who are solely responsible for the facts and accuracy of the material presented. The contents do not necessarily reflect the official views of the Oregon Department of Transportation or the United States Department of Transportation.

The State of Oregon and the United States Government do not endorse products of manufacturers. Trademarks or manufacturers' names appear herein only because they are considered essential to the object of this document.

This report does not constitute a standard, specification, or regulation.

DEVELOPMENT AND SENSITIVITY TESTING OF ALTERNATIVE MOBILITY STANDARDS

TABLE OF CONTENTS

LIST OF TABLES

1.0 OVERVIEW

The Oregon Department of Transportation (ODOT) manages the state highway system under the guidance of the 1999 Oregon Highway Plan (OHP) (*ODOT 1999*). Among other things, OHP policies and actions emphasize efficient use of limited resources. This emphasis, in turn, underlies ODOT's general commitment to sound maintenance of the existing highway system and preservation of its function and safety. OHP Policy 1F establishes mobility standards for state highway facilities to further orient ODOT's planning and programming activities. The mobility standards are expressed as the ratio of the 30th highest hour traffic volume to the facility design hourly capacity (i.e., V/C), and are presented in OHP Tables 6 and 7 (*ODOT 1999: 83-84*).

Among other things, the OHP mobility standards provide a policy foundation that ODOT relies on for coordinating transportation and land use. Although land use decisions are the responsibility of local governments in Oregon, ODOT becomes involved when new or planned development has functional or safety consequences for state highway facilities. Thus, in collaboration with local governments, ODOT employs the OHP mobility standards for a variety of purposes. For example, the mobility standards influence the preparation of transportation system plans (TSPs), corridor plans, and area access management plans (*OAR 734-051*). In the development review process, OHP mobility standards have served as an indirect basis for negotiating traffic mitigation agreements (*ODOT 2008*). Achieving the design life of interchange improvements on the state system is ensured by interchange area management plans' conformance to mobility standards (*ODOT 2006*). Lastly, under the Transportation Planning Rule (TPR) (*OAR 660-012-0060*), the mobility standards provide a basis for evaluating and mitigating the effects of comprehensive plan amendments on state highway performance.

Under the TPR, when it is determined that projected traffic increases associated with a comprehensive plan amendment will have a significant effect on state highway facilities, the effect must be mitigated through planned improvements with identified funding. OHP Policy 1F anticipates circumstances where such mitigation may not be financially or environmentally achievable, resulting in instances where mobility standards will be exceeded. OHP Action 1F6 states that in such instances, ODOT's objective will be to "… avoid further degradation of performance …" (*ODOT 1999: 77*).

The OHP provides an option of requesting alternative mobility standards in circumstances where meeting the mobility standards is not feasible. OHP Action 1F.3 elaborates on possible alternative standards, identifying transportation and land use actions that local governments can take to reduce traffic impacts on state facilities. OHP Action 1F.3 also emphasizes that alternative mobility standards must be relatable to V/C.

ODOT's responsibilities under the TPR were modified by amendments adopted in 2005. Cortright (*2008*) reported that in the subsequent two-year period there were 120 instances involving findings of significant traffic impacts from proposed comprehensive plan amendments in Oregon, with a majority of these instances relating to zoning changes for land located along state highways. Cortright (2008) also observed that a shortage of conventional funding for both state and local capacity improvements was resulting in growing interest in alternative mobility standards and new infrastructure financing mechanisms.

The objective of the present study is to analyze alternative mobility metrics. Although ODOT intends to retain the OHP's V/C-based mobility standards as the preferred option under existing policy, it also expects that it will increasingly encounter instances where comprehensive plan amendments with significant traffic effects will be unable to satisfy the funding conditions of the TPR (*ODOT 2009*). Under these conditions it is important to be able to document the empirical relationship between V/C and metrics representing the diverse range of potential transportation and land use actions covered under the OHP. Without such documentation the Oregon Transportation Commission (OTC), which administers the OHP, cannot determine whether a given set of locally planned actions represents the best achievable outcome for the state highway system in balance with local government objectives.

The intent of the literature review is to identify metrics representing actions and conditions that can be empirically related to V/C. For selected metrics, the literature provides empirical evidence that can be extended to V/C consequences. For other metrics, the research on traffic outcomes is very limited or remains conceptual. While empirical evidence from the literature is desirable, it is generally not sufficient with respect to transferability to Oregon's transportation and land use planning environment. Thus, subsequent effort in this study will be devoted to simulations of the relationship between selected supplemental metrics and V/C using Oregon-calibrated travel demand models.

The remainder of this review is organized as follows. A brief general appraisal of the transportation performance measurement initiative in the United States is presented in Section 2. Section 3 identifies and discusses supplemental performance metrics that hold potential for responding to the needs of this study. Section 4 discusses issues related to the application of supplemental performance metrics. Lastly, conclusions are presented in Section 5.

2.0 PERFORMANCE METRICS IN THE LARGER CONTEXT

Formal experience in the United States with transportation performance measures dates from the Army Corp of Engineers' elementary cost-benefit studies of harbor and river navigation projects in the 1930s (*Quade 1971*). Among states, Oregon's 1937 highway cost allocation study (the nation's first) is considered a pioneering milestone in the use of pavement design and performance information in support of transportation decision-making (*Balducci and Stowers 2008*).

Today, state departments of transportation (DOTs) rely on performance measures to serve diverse objectives and responsibilities. According to Cambridge Systematics et al. (*2009*), the current generation of DOT performance measurement systems evolved from the early 1990s in response to a variety of influences, including:

- the "re-inventing government" movement, which called for greater accountability, transparency, and adoption of the performance-driven management practices of the private sector;
- increasingly complex planning objectives reflecting both formal and informal recognition of transportation's relationship to the natural environment, system user rights and social interests, state economic development policy, the built environment, and community welfare;
- a growing disparity between resource availability and resource needs, which has forced more careful consideration of trade-offs involved in resource allocation decisions;
- increasing flexibility in the allowable uses of federal-aid funds, beginning with the passage of the Intermodal Surface Transportation Efficiency Act of 1991;
- advances in information and intelligent transportation system (ITS) technologies, which has opened up new operations management opportunities, yielded enormous amounts of data, and improved data analysis tools;
- a growing number of state legislative mandates.

One way of fundamentally distinguishing the features of state DOT performance measurement systems is through a hierarchical division of the purposes that the systems are designed to serve. At the first level, performance measures facilitate communication with DOT stakeholders about state highway system conditions. It is likely that all state DOTs utilize performance measures for this purpose.

At the second level of the hierarchy, performance measures are used to support management's programming decisions in allocating resources across operations, maintenance, and improvements. Further, within each of these areas, performance measures can support project prioritization processes. A majority of state DOTs rely (to widely varying degrees) on performance measurement systems for these purposes.

At the third level of the hierarchy, performance measures can serve as a basis for legal or regulatory decisions. For example, access to a transportation facility can be withheld when it can be demonstrated that public safety (as evidenced by safety-related performance measures) would otherwise be compromised (*see Paradyne Corp. v. Florida Department of Transportation 528 So.2d 921 1988*). With respect to land use, Florida's transportation concurrency program conditions local development approval on mitigation that ensures conformance with facility level of service (LOS) standards (*FDCA 2007*). Generally, however, the use of transportation performance measures in a legal or regulatory context is not a very widespread practice among state DOTs.

The need to ensure the integrity and fidelity of performance measures becomes progressively more important from the first to the third level of the hierarchy. Integrity relates to the ability of performance measures to consistently and accurately portray defined phenomena across relevant temporal and geographic scales. Performance measures possess integrity when underlying data quality is high and when space/time inferences made from available data are subject to acceptably low levels of estimation/forecasting error. For example, LOS and V/C are widely considered to be measures with high integrity. Among state DOTs, concerns about integrity (i.e., "data quality") are reported to be a challenge to the adoption and use of transportation performance measures for regulatory purposes (*Cambridge Systematics et al. 2009*).

Fidelity relates to the extent to which given performance measures adequately represent stated concepts or conditions. For example, while V/C and LOS are intended to represent mobility, there are concerns that they do not reflect certain constituent attributes (e.g., reliability) that are also important to highway users (*NCHRP 2007; NTOC 2005*). More fundamentally, it has been argued that accessibility to destinations, rather than mobility, is the more appropriate concept to be represented in metropolitan areas (*Cervero 2005*). However, given that travel time metrics can be related to both mobility and accessibility, these concepts may not be as distinct from each other as they seem to appear.

There is fairly widespread agreement in the literature that LOS and V/C are too narrowly representative of mobility and thus should be supplemented by other metrics (*Cambridge Systematics 2000; Cambridge Systematics et al. 2009; NCHRP 2007; NTOC 2005*). Collectively, supplemental metrics should be capable of representing important contributors to congestion, its spatial and temporal extent, and its consequences (*NCHRP 2007*). It is also recognized that some metrics must either be derived or modeled because they cannot be directly measured (*Cambridge Systematics et al. 2009; NCHRP 2007*).

While a system of multiple metrics will likely represent mobility with greater fidelity, there may also be negative consequences if the metrics supplementing V/C lack its high integrity. This trade-off should be carefully considered where the system is intended to support resource allocation and (especially) regulatory decisions. More generally, Brown (1996) stresses the importance of parsimony, arguing that performance measurement systems should be organized around a "vital few" rather than a "trivial many" set of metrics.

A more general concern relates to the question of whether transportation performance measurement systems contribute to improved outcomes with respect to such benchmarks as accountability, quality of service, economic efficiency, safety, and environmental quality. Given that there has been essentially no research under controlled conditions, the evidence related to this question is mixed. For example, both federal and state transportation agencies have been praised as early adopters and innovative users of performance measurement systems in the public sector (*Cambridge Systematics et al. 2009*). However, another appraisal focusing on transportation and four other public sector functions concluded that "(e)xamples in which performance measures are used to enforce greater accountability are the exception rather than the rule" (*Stecher et al. 2010*). In another case, the Washington Department of Transportation has been characterized as a performance measurement leader among state DOTs (*Cambridge Systematics et al. 2009*). However, a Washington State Auditor's Office evaluation of the Department's transportation improvement program in the Puget Sound region found that congestion measures were not directly factored into the project prioritization process, despite evidence from regional surveys showing congestion to be residents' top transportation concern. Moreover, the Department was unable to document the effect of its Puget Sound region transportation improvements on congestion itself (*WSAO 2007*).

Lastly, a scan sponsored by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (ASHTO) focused on transportation performance measurement systems employed in four industrialized Pacific Rim countries. The scan report (*MacDonald et al. 2004*) concluded that the countries' systems were generally more advanced and strategically engaged in decision-making processes than those commonly found in the United States. Key distinguishing features of the systems reviewed by the scan team include:

- beyond congestion, the systems typically included travel metrics relating to mobility, accessibility, safety, travel time, and travel time reliability;
- customer satisfaction metrics were common;
- performance targets distinguished between urban and rural areas in order to address equity considerations;
- transportation program outcomes were commonly evaluated in relation to defined benchmarks;
- efforts were made (with varying success) to connect resource allocation with performance outcomes;
- a variety of freight performance measures covering travel time, reliability, bottlenecks, terminal access, modal productivity, and regulatory compliance.

3.0 INVENTORY OF CANDIDATE METRICS

The population of performance metrics reported in the literature is quite large, even after accounting for many near-redundancies. However, the identification of candidate metrics becomes more manageable when this study's principal objectives are taken into consideration. These objectives encompass the need to provide a more robust portrayal of mobility, the need to better integrate mobility metrics with metrics representing complementary OHP policies, and the need to empirically relate selected supplemental metrics to V/C with reasonable ease and precision. The resulting roster reflecting these objectives numbers 41 candidate metrics, likely many more than will eventually be considered for further analysis in this study. The candidate metrics are organized into the following six categories:

- Mobility 14 Metrics
- Reliability 8 Metrics
- Land Use/Urban Design 11 Metrics
- Safety 2 Metrics
- Infrastructure 4 Metrics
- Energy/Environment 2 Metrics

The table of selected metrics presented below is the product of a screening process applied by the research team. While the study's objectives served as a basis for screening, evidence from the literature was sometimes lacking and judgments were necessarily involved. Another consideration was the need to anticipate potential scenarios involving multiple metrics. For example, assessing the traffic impacts of transit-oriented or compact development would require metrics representing density, transit access, transit service frequency, land use mixing, and parking. Scenarios involving incident management would draw on recurring/non-recurring congestion, delay, and ITS-related metrics. As these two examples illustrate, the metrics selected should potentially be applicable across a broad range of policy, operations, and design options.

The candidate metrics are presented by category in Table 3.1. The table also presents the following summary information for each metric:

- definition;
- value basis (i.e., the means or method employed to obtain a metric's value), which includes direct measurement, derivation (e.g., using a data tool such as a geographic information system), and modeling;

- modal applicability, including auto, truck, transit bus and rail, bicycle, and pedestrian;
- spatial resolution, including point, segment, zone, district, and area-wide;
- temporal resolution including hourly, seasonal, annual, or self-defined scales;
- references, listing citations from the literature related to the metric's use or empirical relationship to V/C;
- data requirements;
- relationship to V/C, based on empirical evidence associated with such phenomena as trip generation, mode choice, trip length, and other factors;
- examples of the purpose(s) served by given metrics.

Regarding reference applications, a number of the citations listed in Table 3.1 (e.g. *Cambridge Systematics 2000; Cambridge Systematics et al. 2009; Klop and Gunderian 2008; NCHRP 2007; NTOC 2005*) provide general insight on the logic for including given metrics in a highway performance measuring system. Collectively, these citations also document a large array of performance metrics serving a variety of purposes. However, they rarely address the relationship between a given metric and a defined outcome, such as V/C. Thus, other citations addressing the empirical relationship between V/C (or its constituent attributes) and each metric are included where such evidence could be found. In some instances, such references may have focused on a close variant of the metric defined in the table. An effort was also made to identify studies that synthesize published empirical findings. For example, Ewing and Cervero's (*2010*) meta-analysis proved very helpful in documenting the relationship between VMT and selected land use and urban design metrics from the substantial literature on that subject. The following discussion proceeds according to the organization of Table 3.1.

3.1 MOBILITY METRICS

V/C is included in Table 3.1 as a reference metric. Collectively, the remaining 13 metrics represent temporal, spatial, and operational dimensions of mobility. Conceptually, all are relatable to V/C.

While V/C is a very useful metric for transportation planning, engineering and design, it has been argued that it is less reflective of travelers' mobility perspectives (*NCHRP 2007*). Both personal travelers and freight carriers are concerned about delay (generally), the geographic and temporal extent to which their travel is subject to delay, and the real and implicit monetary costs they bear as a result of delay. Thus, the widely-recognized *Urban Mobility Report,* published annually by the Texas Transportation Institute, includes four of the mobility metrics listed in Table 3.1: Recurring Delay (along with total and non-recurring delay), Congestion Duration, Congestion Extent, and Percent of Congested Travel. Together, these metrics provide a fairly robust representation of congestion and its consequences for travelers.

With its primary focus on delay, the *Urban Mobility Report* is also able to consistently assess the effects of alternative congestion-relieving treatments related to operational improvements and transit provision. In 2007, operational and transit-related "avoided delays" were estimated to amount to nearly 23% of total delay across the 439 urban areas covered in the report (*Schank and Lomax 2009*). Separately, analysis by Chin et al. (*2002*) indicates that potential further reductions in delay from operational improvements are large.

Table 3.1: Characteristics of Supplemental Performance Metrics

Performance Metric	Definition	Value Basis	Mode(s)	Spatial Resolution	Temporal Resolution	References	Data & Tools Required	Relation to V/C	Purpose
Mobility									
V/C Ratio (Reference Metric)	Ratio of traffic volume to facility capacity	Measured Modeled	Auto Truck	Point; Segment	Hourly	Cambridge Systematics et al (2009); Klop & Guderian (2008); ODOT (1999; 2004; 2009); Wray (1998)	Hourly traffic volumes; Facility design capacity; HCM	Same	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
LOS	Progressive letter grades A-F used to stratify performance measure chosen to determine LOS (V/C, delay, density)	Measured Modeled	Auto Truck Bus Rail Bike Pedestrian	Point; Segment Facility	Hourly	Cambridge Systematics et al (2009); FDCA (2007); FDOT (2009); GDOT (No date); TRB (2000); VDOT (No date)	Generally hourly traffic volumes, capacity, inventory data; HCM	May be used to categorize V/C (and other measures)	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
Travel Time	Travel time required to traverse a segment, facility (all modes), or a region (most relevant to freight)	Measured Modeled	Auto Truck Bus Rail Bike Pedestrian	Segment; Facility	Self-defined (Minutes)	Cambridge Systematics (2009); Gregor (2004; 2009) NTOC (2005)	Measured travel times (pavement detectors, vehicle onboard devices); Modeled networks;	Non-linear positive relation to V/C up to point of jam density	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
Waiting Time	Out-of-vehicle time spent waiting by transit passengers, including transfer time	Measured Modeled	Bus Rail	Segment; Facility	Self-defined (Minutes)	Strathman et al. (1999)	On-board surveys; transit schedules; modeled transit networks	Directly related to V/C through mode diversion	Facility operations/sizing; Evaluating system plan objectives
VMT	Vehicle miles traveled within a specified area and time period	Derived; Modeled	Auto Truck Bus Rail	Facility; District to Area-wide	Hourly Daily Annual	Cambridge Systematics et al (2009); Klop & Guderian (2008) NCHRP (2007)	Modeled trip tables; Network based distance skims	Auto, Truck - directly related; Bus/Rail – inversely related	Land use impact assessment; Evaluating system plan objectives
VHT	Vehicle hours traveled within a specified area and time period. May be volume-weighted (autos), or weighted by commodity tonnage or value (trucks)	Derived Modeled	Auto Truck Bus Rail	Facility; District to Area-wide	Hourly Daily Annual	NTOC (2005)	Measured travel times (pavement detectors, vehicle onboard devices); Modeled networks; Shipment data needed for freight	Auto, Truck - directly related; Bus/Rail – inversely related	Land use impact assessment; Evaluating system plan objectives
Recurring Delay	Vehicle delays that are repeatable for the current time of day, day of week, and day type below a threshold (e.g. 70th percentile)	Measured Derived Modeled	Auto Truck Bus	Point; Segment; Facility	Hourly	Cambridge Systematics et al (2009); Klop & Guderian (2008); NTOC (2005)	Travel times by time segment (e.g., 1-hour, averaged over 30 days); ITS sources; DTA	Recurring delay generally increases with increases in V/C	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives

Person Throughput	Number of persons (vehicle occupants, pedestrians, and cyclists) traversing a segment or facility in one direction per unit time (or crossing a screen/cordon line)	Measured Derived Modeled	Auto Bus Rail Bike Pedestrian	Point; Segment; Facility; Multi-modal corridor	Hourly Daily Annual	Klop & Guderian (2008); NCHRP (2007); NTOC (2005); RITA (2004)	Auto counts with surveyed occupancy data; Transit passenger counts; Bike and Pedestrian counts	Holding occupancy constant, directly related; holding vehicles constant, inversely related	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
PHT	Person hours of travel within a specified area and time period, sometimes expressed in terms of excess delay.	Modeled	Auto Bus Rail Bike Pedestrian	Segment; Facility; Multi-modal corridor; District to Area-wide	Hourly Daily Annual	Cambridge Systematics (1998); Capital District Transportation Committee (2007)	Modeled trip tables; Vehicle occupancy assumptions; Network based distance skims	Generally, directly related to V/C, but will vary depending on non-auto mode utilization	Land use impact assessment; Evaluating system plan objectives
Mobility Index	PMT/VMT*Average Speed	Modeled	Auto Bus Rail	Segment; Facility; Multi-modal corridor; District to Area-wide	Hourly Daily Annual	Bertini (2005a); Cambridge Systematics (2000); Cambridge Systematics et al (2009)	Modeled trip tables, network based distance skims, surveyed occupancy rates, modeled travel time skims	Generally inversely related to V/C	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
Trip Length Distributions	Frequency distribution of trips by 1-mile bins for different purposes and by different modes.	Modeled	Auto Truck Bus Rail Bike Pedestrian	Zonal; District to Area-wide	Daily Annual	Trip length distributions are a common product of travel demand models	Household surveys; OD surveys; Establishment surveys; modeled trip tables and networks	Local effects on V/C will vary	Land use impact assessment; Evaluating system plan objectives
Congestion Duration	Time expressed in hours that a directional highway segment remains congested, subject to speed threshold definition of "congested condition"	Measured Modeled	Auto Truck Bus	Segment Facility	Hourly	Cambridge Systematics et al (2009); Bertini (2005a); NTOC (2005)	Travel speeds by time interval	Congestion is usually defined by speed or travel time thresholds, which positively correlate with V/C	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
Congestion Extent	The length of a freeway segment, by direction, that experiences speeds below 'X' mph for 'Y' minutes or more; miles of roadway within an area and time for which average travel times are X% longer than unconstrained travel times	Measured Modeled	Auto Truck Bus	Segment Facility; District to Area-wide	Hourly Daily	Bertini (2005a); NCHRP (2007); NTOC (2005)	Travel speeds by time interval, segment lengths	Congestion is usually defined by speed or travel time thresholds, which positively correlate with V/C	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives

Percent of Congested Traffic	Ratio of congested VMT to total VMT; Total VMT = total traffic volume * the length of the road section (for the time period of interest) Congested VMT = Traffic volume * the length of the road section that occurs below a present threshold (for the time period of interest)	Derived	Auto Truck Bus	District to Area-wide	Hourly Daily Annual	Cambridge Systematics et al (2009); MDOT (2005); NTOC (2005)	Measured or modeled volumes and speeds by time interval, segment lengths	Congestion is usually defined by speed or travel time thresholds, which positively correlate with V/C	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
Queues	Point (Frequency of Spillback) - Proportion of time when queue spills back beyond threshold; Area - Percentage of intersections where point spillback is a problem - occurs 'X' times during specified time	Derived Modeled	Auto Truck Bus	Point Segment; District to Area-wide	Hourly Daily Annual	Bertini (2005b); Cambridge Systematics et al (2009); NTOC (2005)	Segment lane geometry, access/egress points, traffic control operations (timing plans, metering) directional volumes	Directly related to V/C	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
Reliability									
Non-recurring Delay (General)	Vehicle hours of delay in excess of recurring delay for a given time of day, day of week, and day type	Measured Derived Modeled	Auto Truck Bus Rail	Segment Facility; District to Area-wide	Hourly Daily Annual	Cambridge Systematics et al (2009); Hallenbeck et al. (2003); NJTPA (No date); NTOC (2005)	Travel times by time segment (e.g., 1-hour, averaged over 30 days); ITS sources; DTA; Transit schedules	Auto, Bus, Truck: directly related to V/C; Rail: no relation to V/C	Facility operations/sizing; Evaluating system plan objectives
Non-recurring Delay (Incident Occurrence and Management)	Average time required to clear an incident	Measured Derived Modeled	Auto Truck Bus	Segment Facility; Area-wide	Annual	Cambridge Systematics et al (2009); Carson et al. (1999); Dailey (2006) NCHRP (2007) NTOC (2005)	Time of incident, response arrival time, clearance time, return to normal flow	Relation to V/C unclear	Facility operations/sizing; Evaluating system plan objectives
95^{th} Percentile Travel Time	Travel time corresponding to the 95^{th} highest out of 100 (or 19^{th} highest out of 20)	Measured Derived Modeled	Auto Truck Bus Rail Bike	Facility; District to Area-wide	Hourly Daily	Cambridge Systematics et al (2006; 2009); FHWA (2007); NCHRP (2007); Small (1982)	Travel times by time segment (e.g., 1-hour, averaged over 30 days); ITS sources; DTA	Generally, directly related to V/C, but will vary dramatically when traffic densities reach critical thresholds	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives

Buffer Index	Percent of extra travel time travelers add to expected travel time to ensure on-time arrival "X"% of time, e.g., (95th percentile travel time – mean travel time)/ mean travel time	Measured Derived Modeled	Auto Truck Bus Rail Bike	Facility; District to Area-wide	Hourly Daily	Cambridge Systematics et al (2006; 2009); FHWA (2007);McMullen and Monsere (2010) NCHRP (2007); Small (1982)	Travel times by time segment (e.g., 1-hour, averaged over 30 days); ITS sources; Modeled congested travel time skims, DTA; Transit schedules	Generally, directly related to V/C, but will vary dramatically when traffic densities reach critical thresholds	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
Planning Time Index	Total travel time travelers should expect to take to ensure on-time arrival relative to free-flow conditions "X"% of time, e.g., (95th percentile travel time – free-flow travel time)/ free-flow travel time	Measured Derived Modeled	Auto Truck Bus Rail Bike	Facility; District to Area-wide	Hourly Daily	Cambridge Systematics et al (2006; 2009); FHWA (2007); NCHRP (2007); Small (1982)	Travel times by time segment (e.g., 1-hour, averaged over 30 days); ITS sources; Modeled free-flow travel time skims, DTA; Transit schedules	Generally, directly related to V/C, but will vary dramatically when traffic densities reach critical thresholds	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
On-time Performance	% On-time performance (within industry thresholds)	Measured Derived	Truck Bus Rail	Facility (transit line); District to Area-wide	Annual	Cambridge Systematics et al. (2009); Strathman and Hopper (1993)	Transit or truck arrival time data; from ITS or internal records	Inversely related to V/C	Facility operations/sizing; Evaluating system plan objectives
Fluctuations in Travel Times	Travel time variation across 'X' minute intervals; coefficient of variation = standard deviation / mean	Measured Derived	Auto Truck Bus Rail	Point; Segment	Hourly Daily	Cambridge Systematics (2000); NTOC (2005)	Travel times by time segment (e.g., 1-hour, averaged over 30 days); ITS sources	Expect fluctuation to be lower for high values of V/C	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
Fluctuations in Traffic Volumes	Traffic volume variation across 'X' minute intervals; coefficient of variation = standard deviation / mean	Measured Derived	Auto Truck Bus Rail	Point; Segment	Hourly Daily	Cambridge Systematics (2000); NTOC (2005)	Volumes by time segment(e.g., 1-hour, averaged over 30 days); ITS sources	Expect fluctuation to be lower for high values of V/C	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
Land Use/Urban Design									
Accessibility to Destinations	Percent of population living within "X" miles or "Y" minutes of defined destinations, by trip purpose and mode	Derived Modeled	Auto Bus Rail Bike Pedestrian	Zonal; District; Area-wide	Hourly Daily	Bhat et al. (2002); Cambridge Systematics (2000); Cambridge Systematics et al (2009); Cervero (2005); Ewing & Cervero (2010)	Population data; Employment data by sector; Transit network data; Detailed street network data; Travel time skims	V/C may increase or decrease locally depending on net effects of accessibility on trip generation and mode choice	Land use impact assessment; Evaluating system plan objectives

Accessibility to Employment and Population	Composite formulas for defining access to job or retail markets by single modes or composite modes. Gravity-model-like formula with travel cost/distance-decay relationship, or within "Y" minute buffer	Derived Modeled	Auto Bus Rail Bike Pedestrian	Zonal District Area-wide	Hourly Daily	Reiff and Gregor (2005)	Employment data; Transit network data; Detailed street network data; Travel time skims	V/C may increase or decrease locally depending on net effects of accessibility on trip generation and mode choice	Land use impact assessment; Evaluating system plan objectives
Accessibility to Transit	Percent of population that can access fixed-route transit within "X" miles or "Y" minutes	Derived	Bus Rail	Zonal; District; Area-wide	Hourly Daily	Bhat et al. (2002); Cambridge Systematics (2000); Cambridge Systematics et al (2009); Ewing & Cervero (2010)	Geo-coded population data; Transit stop and station data	Inversely related: Holding density constant, auto trip generation decreases with increasing access to transit	Land use impact assessment; Evaluating system plan objectives
Accessibility to Freight Terminals	Number of industry-specific jobs (as proxy) within "X" miles or "Y" truck travel time minutes of port or intermodal facilities	Derived Modeled	Truck	District; Area-wide; Statewide	Hourly Daily	McMullen and Monsere (2010); MacDonald et al. (2004)	Geo-coded locations of ports and intermodal terminals; industry-specific employment data by zone; network travel times	Accessibility would generally increase with V/C, but local effects may differ	Land use impact assessment; Evaluating system plan objectives
Bike/Pedestrian Network Circuitousness	Ratio of shortest network path distance to shortest Euclidean distance	Measured	Bike Pedestrian	Zonal; District; Area-wide	Annual	Dill (2004)	GIS street network, Transit routes; Bicycle facility shapefiles; Sidewalk shapefiles	Generally inverse: Reduces V/C through a reduction in VMT and lower auto trip generation	Land use impact assessment; Evaluating system plan objectives
Street Connectivity	Index measured as the ratio of intersections to lane-miles for a given area, or neighborhood link-to-node ratio	Measured	Bike Pedestrian	Zonal; District; Area-wide	Annual	Chapman & Frank (2004) City of Portland (1998); Ewing & Cervero (2010); FHWA (1999); Hedel & Vance (2007) Reiff & Gregor (2005)	GIS street network, Transit routes; Bicycle facility shapefiles; Sidewalk shapefiles	Generally inverse: Reduces V/C through a reduction in VMT and lower auto trip generation	Land use impact assessment; Evaluating system plan objectives
Land Use Mix	Multi-family, Retail and Services, Office, Entertainment, Institutional, and Industrial land use relative to Single Family use within a defined area	Derived	Auto Truck Bike Pedestrian	Zonal; Multi-modal corridor; District; Area-wide	Annual	Ewing & Cervero (2010); Frank and Pivo (1995); Hess et al. (2001)	Geo-coded parcel level land use data; Floor area data	V/C may increase or decrease depending on net trip generation, length and mode choice changes	Land use impact assessment; Evaluating system plan objectives

Population and/or Employment Density	Structures: Square footage of improvements divided by district area; Households and workers: Persons divided by district area.	Derived	Auto Truck Bike Pedestrian	Zonal; Multi-modal corridor; District; Area-wide	Annual	Cervero & Murakami (2010); Ewing & Cervero (2010); Frank & Pivo (1995); Handy et al. (2002);	GIS parcel data; Zonal & area wide population & employment estimates	V/C may increase or decrease locally with increasing density depending on its net effects on trip generation, length and mode choice	Land use impact assessment; Evaluating system plan objectives
Off/On-Street Parking V/C	V/C of parking facilities within a specified area (e.g., CBD)	Measured	Auto Bus Rail Bike Pedestrian	Segment; Facility; Multi-modal corridor; District; Area-wide	Hourly Daily	Kuzmyak et al. (2003) Young et al. (1991);	Parking space inventory; Peak/Off-Peak utilization counts	V/C of parking supply will have positive correlation with adjacent segment or facility V/C	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
Transit Station Parking V/C	V/C of parking facilities for bus & rail park-and-ride	Measured	Auto Bus Rail Bike Pedestrian	Multi-modal corridor; District; Area-wide	Hourly Daily	Klop & Gunderian (2008); Turnbull et al. (2004)	Parking space inventory; Peak/Off-Peak utilization counts	V/C of parking supply will have positive correlation with adjacent segment or facility V/C, but negative correlation with V/C on area-wide level due to mode diversion	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives
Bike Storage Facility Utilization	V/C of bike lockers or other facilities	Measured	Bike	Multi-modal corridor; District; Area-wide	Hourly Daily	Kuzmyak et al. (2010)	Parking space inventory; Peak/Off-Peak utilization counts	V/C of bike storage facilities should have loose inverse correlation with highway V/C due to mode diversion	Land use impact assessment; Evaluating system plan objectives
Safety									
Crash Rates	Total, fatality, injury, and non-injury crashes per VMT or PMT	Measured	Auto Truck Bus Rail Bike Pedestrian	Point; Segment; District; Area-wide	Annual	Cambridge Systematics et al (2009); Dickerson et al. (1998); Golob et al. (2004) NCHRP (2007); USDOT (2003); Wang et al. (2009)	Crash counts by severity by mode; VMT/PMT by mode; HSM	Generally, crash rates increase with V/C	Facility operations/sizing; Land use impact assessment; Evaluating system plan objectives

Crime	Crimes per 1,000 transit passengers	Measured	Bus Rail	Point; Segment; District; Area-wide	Annual	Cambridge Systematics (2000); Needle & Cobb (1997); Sacramento Regional Transit (2008)	Geo-coded crime data; Transit passenger counts	None	Evaluating system plan objectives
Infrastructure									
Freeway Lane-Miles With ITS	System extent of deployment of ITS technologies	Measured	Auto Truck Bus	Facility; Segment; Area-wide	Annual	Cambridge Systematics (2000); Mannering (1989); NCHRP (2007)	Inventory data	Inversely related to V/C (ITS facilitates operational improvements affecting volumes or effective capacity)	Evaluating system plan objectives
Total Freeway Lane-Miles	Total freeway lane-miles	Measured	Auto Truck Bus	Area-wide	Annual	Cambridge Systematics (2000); Cervero (2002)	Inventory data	Inversely related to V/C (e.g., freeway capacity additions)	Evaluating system plan objectives
Transit Supply	Revenue hours/miles of service provided; Service frequency/average headway	Measured	Bus Rail	Facility Segment Zonal District Area-wide	Hourly	Evans et al. (2004)	Archived transit operations data	Inversely related to V/C	Evaluating system plan objectives
Bicycle Lane-Miles	Miles of striped bicycle lanes	Measured	Bike	Facility Segment Zonal District Area-wide	Annual	Pucher et al. (2010)	Inventory data	Uncertain	Evaluating system plan objectives
Energy/Environment									
Fuel Consumption per VMT or PMT	Fuel consumption per VMT or PMT	Derived Modeled	Auto Bus Rail	Area-wide	Annual	Cambridge Systematics et al (2009); FHWA (2008); Greene (1998); NCHRP (2007); Stecher et al. (2010)	VMT & fuel consumption rates by vehicle class	Loosely directly related to V/C	Land use impact assessment; Evaluating system plan objectives
Tons of Pollutants Generated	Tons of carbon monoxide, nitrogen oxides, sulfur dioxide and particulate matter generated	Derived Modeled	Auto Bus Rail	Area-wide	Annual	Cambridge Systematics (2000); Cambridge Systematics et al (2009); Flanigan & Howard (2008); NCHRP (2007); Stecher et al. (2010)	VMT & emission rates by vehicle class	Loosely directly related to VMT and V/C	Land use impact assessment; Evaluating system plan objectives

The travel time and trip length distribution metrics jointly reflect motorists' exposure to congested travel. They also provide a means of assessing selected congestion mitigation strategies. For example, holding trip lengths constant, the effects of capacity or operational improvements can be examined through changes in travel times. Alternatively, holding travel times constant, the effects of scenarios focused on improving accessibility can be examined through changes in the distribution of trip lengths.

ODOT selected V/C to represent the OHP mobility standard following an evaluation of 11 alternative metrics against 8 criteria (*ODOT 1998*). Three of the mobility metrics listed in Table 3.1 were among those evaluated: Vehicle Miles Traveled (VMT), Delay, and Person Throughput. The evaluation concluded that the greatest distinctions between V/C, VMT, Delay, and Person Throughput were concentrated in the following four areas:

- V/C can be much more consistently applied across diverse circumstances and jurisdictions than VMT, Delay, or Person Throughput.
- V/C serves as a somewhat better indicator of intercity mobility than VMT or Person Throughput, although it fares somewhat worse than Delay.
- V/C offers a much better basis of support for operations decisions (e.g., in the areas of signal control and access management) than VMT or Person Throughput, and a somewhat better basis than Delay.
- V/C can be forecasted with much greater confidence than Person Throughput, and somewhat greater confidence than VMT or Delay.

In summary, the 1998 ODOT study concluded that the greatest advantages of V/C over alternative performance metrics were its usefulness in operational analysis of specific facilities and the greater confidence in its inherent integrity. It was also recognized that other mobility metrics can be valuable in selected contexts. Delay and Person Throughput, for example, would be better metrics for user benefits assessment, while VMT or VHT would be more appropriate metrics for evaluating air quality impacts.

3.2 RELIABILITY METRICS

There is growing agreement on the need to include reliability metrics in examining highway performance (*NCHRP 2007; NTOC 2005*). Table 3.1 includes eight metrics related to reliability. Two of the metrics provide general and operational representations of non-recurring delay. Three additional metrics address travel time variability. The remaining three metrics focus on travel schedule reliability.

Non-recurring delay represents excess time lost beyond that due to recurring delay for a given day and time period. Schrank and Lomax (*2009*) estimate that non-recurring delay accounted for 54% of total personal delay among 439 urban areas in 2007. The relative importance of non-recurring delay also varies with V/C. At low V/C values, virtually all delay is attributable to non-recurring causes, while at high V/C values its relative contribution to total delay falls well below the average figure reported by Schrank and Lomax (*2009*). Regarding the relative importance of its various sources, Hallenbeck et al. (*2003*) found that lane-blocking incidents accounted for 10-35% of total non-recurring delay in the Puget Sound region. Thus, incident management programs could play an important part in reducing delay associated with non-recurring congestion.

The metric described as fluctuations in traffic volume measures the standardized variation in traffic volume for defined time periods. The main benefit from standardization (which yields a coefficient of variation) is in the clear interpretation of the metric across different types of facilities and over distinct time frames and traffic volumes.

The buffer index tends to increase with V/C, reflecting the increasingly uncertain delay consequences of the growth of recurring and non-recurring congestion. For example, Cambridge Systematics et al. (*2006*) present findings from a 4-city analysis showing the buffer index increasing in near-linear (but less than proportionate) fashion with increases in the travel time index. Thus, while the absolute size of the buffer index would increase with V/C, its size relative to expected travel time (i.e., the mean or median, depending on the specific metric) would decline.

The on-time performance metric is an important performance consideration in circumstances involving scheduled transportation services, such as transit and freight pick-up/delivery. Although less explicit, on-time performance is also relevant in personal auto travel, where commuters face penalties (sometimes directly) for failure to arrive at given work start times and where non-work travelers experience disutility for deviating from desired arrival times.

Incident management programs seek to reduce the time required to clear an incident and allow traffic to return to its normal flow. Incident response teams (IRTs) generally give highest priority to incidents that block travel lanes. IRTs also usually patrol during peak periods and respond to minor incidents when possible. Carson et al. (1999) evaluated Washington DOT's incident response program in the Puget Sound region. They estimated a 21-minute decline in duration for IRT-served incidents, which translated into estimated annual vehicle delay savings ranging from $3-9 million (as compared to annual program costs of about $700,000).

Research on non-recurring congestion has shown increasing interest in the role of weather, both in terms of its effects on speeds and in terms of its effects as a determinant of traffic incidents (*Dailey 2005*). Also, beyond the standard operational focus on incident management, there has been growing attention given to emergency management conditions (*NTOC 2005*).

3.3 LAND USE/URBAN DESIGN METRICS

Among other objectives, OHP Policy 1B (*Land Use and Transportation*) promotes compact urban development. The land use and urban design metrics in Table 3.1 provide a means of empirically relating various characteristics of compact urban development to Policy 1F's mobility standards.

Population and employment density are the most basic indicators of compact urban development. Ewing and Cervero's (*2010*) meta-analysis includes these metrics, and they report their associated weighted VMT elasticities. Their reported per capita/household VMT elasticity for household/population density is -0.04, as derived from the nine studies included in their analysis. Thus, in this case, a 10% increase in household/population density results in an estimated -0.4% reduction in VMT per person/household. Alternatively, their reported elasticity for employment density is 0.00, based on six studies. This latter finding may reflect other research indicating that while the general dispersion of employment has lengthened commutes for many central urban residents, it has also shortened the commutes of suburban residents (*Gordon et al. 1989*).

As previously noted, mobility and accessibility are related through VMT. Ewing and Cervero (*2010*) report per capita/household VMT elasticities of job accessibility metrics for both transit and auto modes. For auto accessibility the elasticity is -0.20, while for transit accessibility the elasticity is -0.05. Accessibility to destinations by transit depends in part on the extent to which transit is accessible to travelers. Ewing and Cervero's (*2010*) reported per capita/household VMT elasticity with respect to transit access is -0.05.

Multiple use zoning, or land use mixing, facilitates travel by alternative modes and is expected to result in shorter trips. Ewing and Cervero's (*2010*) meta-analysis covers 10 studies employing entropy-based land use mix metrics. They report a weighted mean per capita/household VMT elasticity of -0.09 from the results of these studies.

Connectivity metrics reflect the extent to which travel distances between points can be minimized. The metric in Table 3.1 uses intersection density to represent connectivity, as examined by Chapman and Frank (*2004*). Alternatively, studies have employed metrics using street density to represent connectivity (*Hedel and Vance 2007; Reiff and Gregor 2005*). Six empirical studies employing either an intersection or street density metric were covered in Ewing and Cervero's (*2010*) meta-analysis. Their reported weighted mean per capita/household VMT elasticity from these studies was -0.12.

Ewing and Cervero (*2010*) observe that many of the VMT elasticities obtained in their meta-analysis are quite small, which implies that the land use and urban design features represented by the respective metrics in Table 3.1 have limited V/C consequences. However, they also emphasize that effective comprehensive planning usually produces changes across multiple land use and urban design metrics. They thus note that the VMT elasticity effect of comprehensive planning is additive across the affected metrics. Depending on the land use and urban design outcomes of implemented plans, this composite VMT elasticity could be large. For example, transit oriented development (TOD) combines a number of travel-reducing and alternative mode-favoring measures, including higher development density, mixed use zoning, good transit access, enhanced transit supply, and parking maximums. Cervero and Arrington (*2008*) recorded weekday vehicle trip generation in 17 TODs located in five metropolitan areas. Overall, their recorded trip generation rates were 44% lower that the rates reported in the ITE *Trip Generation* manual (*ITE 2003*). Their study included five Portland TODs, and trip generation rates for these developments were 41% below the ITE rate.

Parking availability and cost are strong determinants of mode choice, especially for work trips (*Strathman and Dueker 1996; Willson 1991*). Cities are slowly moving away from enforcing minimum parking requirements on new development in core areas in an effort to promote transit use and improve air quality (*Dueker et al. 1998; Kuzmiak et al. 2003*). Kain (*1994*) concludes that such policies and regulations ought to be in place before congestion pricing is considered.

Park and ride facilities dedicated to transit are often employed to attract heavy and light rail "choice" riders with longer commutes. Given the greater spacing between rail stations, park and ride lots allow commuters to access transit by auto where conditions for providing feeder access by bus are impractical or uneconomic (*Turnbull et al. 2004*). Park and ride facilities can also serve as a staging location for car or vanpooling activity. The main highway performance benefit of these facilities is the reduction in congestion on routes leading to rail destinations, typically urban core commercial centers. The propensity to choose commuter rail is adversely affected as lot utilization approaches saturation, and is also adversely affected by the pricing of lot use (*Turnbull et al. 2004*).

Similar to the TOD example, transportation demand management (TDM) programs commonly include features represented by multiple metrics. For example, TDM measures may extend to the adoption of parking maximums and market pricing of parking, extension of employee transportation benefits beyond employer-paid parking to provision of transit passes and bicycling facilities, and provisions for telecommuting and guaranteed rides (*Kuzmyak et al. 2010*). In combination, these TDM features have contributed to increased use of alternative modes and reductions in congestion.

3.4 SAFETY METRICS

Safety is an important transportation objective in its own right. Crash rates disaggregated by mode, type, severity, and road class are typically included among highway performance measures. Research shows that crash rates increase substantially as traffic flow approaches saturation (*Dickerson et al. 1998; Golob et al. 2004*). One would expect fatal/severe injury crash rates to be lower in congested than in free flow conditions (given reduced speeds), but the corresponding evidence is mixed (*Wang et al. 2009*). With respect to highway performance, higher crash rates contribute to an increase in the incidence of non-recurring congestion, thus worsening reliability.

Safety is also important for transit. However, crash rates among transit modes are far lower than the rates for passenger and commercial vehicles (*APTA 2009*). Alternatively, transit rider surveys find that personal safety on vehicles and in the vicinity of stops and stations is an important customer concern (*Potts 2002*). Although it is generally accepted that the incidence of crime negatively affects the demand for transit (*Needle and Cobb 1997*), empirical studies documenting this relationship are lacking. Thus, the empirical relationship between this metric and V/C is uncertain.

3.5 INFRASTRUCTURE METRICS

Given that highway capacity is directly represented in V/C, an increase in lane-miles can be expected to reduce V/C. However, capacity improvements can also increase subsequent traffic volumes at both the system and facility levels by releasing latent demand and by altering route choices. Cervero (*2002*) surveyed empirical studies of latent demand responses to capacity increases and found associated long run VMT elasticities ranging from .3 to .6.

Table 3.1 does not identify infrastructure metrics representing capacity improvements for site-specific facilities, such as intersections and interchanges. Clearly, such improvements enhance mobility, reliability and safety. However, individual metrics would be unable to adequately represent multiple capacity-related design elements of such facilities (e.g., ramp/overpass capacities, signalization, and access control features of interchanges). Generally, given specific design information about a facility improvement, a metric or set of metrics could be identified to represent a change in facility capacity. Thus, rather than attempt to identify a list of metrics that could potentially be employed across varied site-specific design contexts, we note that metrics exist to represent site-specific facility capacity changes.

Transit supply (capacity) can be represented by revenue hours or revenue miles of service. Generally, transit demand is more responsive to supply than to fare changes. Demand elasticities related to supply changes vary by transit mode, base level of service, area economic conditions, and operating/price conditions of non-transit modes. A literature survey by Evans et al. (*2004*) found transit supply elasticities ranging from .3 to 1.5. Thus, transit supply is inversely related to V/C.

Miles of striped bicycle lanes serve as one proxy for bicycle infrastructure capacity. Pucher et al. (*2010*) reviewed 19 empirical studies relating bicycle use to the supply of bicycle lanes. Results of these studies were mixed, with some reporting a significant positive relationship between capacity and use, and others finding no relationship. Given that a positive relationship exists, another issue concerns the extent to which increases in bicycle use substitute for the use of other transportation modes. If the principal substitute for bicycle use is transit, for example, the consequent effect on V/C would be negligible. Evidence of modal substitution effects in this context is lacking. For these reasons, the empirical relationship between bicycle lane miles and V/C is characterized in Table 3.1 as uncertain.

Deployment of ITS technologies has resulted in a variety of highway operations benefits, affecting commercial vehicle mobility (in preclearance and automatic vehicle location systems applications), incident management, traffic management (in signal control systems and ramp metering improvements), and traveler information (in real time navigation systems and in the reporting of traffic and other conditions). Traveler information can help to mitigate the effects of non-recurring congestion by influencing route choice and trip scheduling decisions. Mannering (*1989*) found that route choice decisions were highly sensitive to information about changes in relative travel times, while trip scheduling decisions were much less sensitive. His latter finding likely reflects the real and implicit penalties that travelers face in altering their travel schedules, especially for work-related trips (*Small 1982*).

A basic difference in ITS deployment in the transit industry is that vehicles are primarily being instrumented rather than facilities. Data from automatic vehicle location systems are used to produce more reliable transit schedules and are also used in real time applications, such as in broadcasts of predicted vehicle arrival times at stops and stations. Both the improvements in schedule reliability and reductions in customer waiting time uncertainty have positive consequences for transit demand and customer satisfaction (*Furth et al. 2006; Strathman et al. 2008*). Through the resulting increases in ridership, ITS applications in the transit industry have thus contributed to reducing V/C.

3.6 ENERGY/ENVIRONMENT METRICS

Both energy use and emissions are end consequences of VMT, and actions that have been taken to affect either metric have had varying effects on V/C. Nevertheless, these metrics have been included because they are considered to be among the best examples linking transportation performance measures to benchmarks, and, in turn, relating performance to economic sanctions and resource allocation decisions (*Stecher et al. 2010*).

With respect to energy efficiency, the corporate average fuel economy (CAFÉ) standards first authorized in the Energy Policy and Conservation Act of 1975 have, over the past three decades, established progressively higher efficiency benchmarks that must be met by auto manufacturers. Failure to meet the CAFÉ standard results in a penalty ($5.50 per vehicle per .1 mpg exceeding the standard) that the manufacturer must pay. Between 1975 and 2008 energy use per vehicle mile for automobiles and light trucks has fallen 39% and 42% respectively (*ORNL 2010*), at least partly in response to the CAFÉ standards. Also, given that emission of carbon dioxide (a primary greenhouse gas) is a direct function of fuel consumption, the CAFÉ standards have also produced climate benefits.

The CAFÉ standards have been criticized because they have had little effect on VMT trends (*Greene 1998*). Critics argue that energy efficiency improvements could have been achieved by increasing the gas tax and that, unlike CAFÉ standards, a gas tax would have also reduced travel demand. While Greene (*1998*) agrees with this argument in principle, he also observes that strong public resistance has made a gas tax increase (sufficient to achieve the same efficiency improvement) a much less viable alternative.

The Clean Air Act Amendments of 1990 set more rigorous transportation modeling requirements for areas that are out of compliance with EPA air quality standards. The amendments required the use of enhanced modeling to demonstrate that transportation improvement programs are facilitating progress toward compliance in nonattainment areas. Moreover, nonattainment areas must demonstrate progress toward compliance to qualify for federal transportation funds. Thus there is a strong economic incentive for affected improvement programs to emphasize a mix of VMT-reducing and congestion-relieving projects. Separately, the federally-sponsored Congestion Mitigation and Air Quality Improvement Program (which covers both maintenance and nonattainment areas) has also resulted in an emphasis on VMT-reducing transportation improvement projects to improve air quality (*TRB 2002*).

4.0 USE OF SUPPLEMENTAL METRICS: CONTEXTUAL ISSUES

The metrics presented in Table 3.1 and discussed in Section 3 vary across several dimensions--value basis, spatial and temporal resolution, and usefulness for different types of evaluation. Some metrics, such as the V/C ratio, are clearly appropriate for evaluating operational performance. Such metrics can be appropriately analyzed at the facility level. Viewed in isolation, however, they cannot directly account for the performance of other facilities and other travel modes. Other metrics, such as "accessibility to destinations," are clearly more appropriate for evaluating system performance and the achievement of system planning objectives. While such metrics employ system-level measurement and can directly consider multiple modes, they also can obscure potentially important facility level effects. Thus, there are obvious tradeoffs in metric perspectives. At one end, focusing on an individual facility may ignore the need to address system-wide objectives. At the other end, focusing on system-level performance may come at the detriment of ignoring performance on selected facilities.

Evaluating comprehensive plan amendments is particularly difficult because it can encounter the need to reconcile issues involving these two extremes. Plan amendments are typically proposed to advance system-oriented goals, such as economic development or compact development. However, these amendments may have both system level and local effects on specific transportation facilities. Ideally, when evaluating plan amendments, a natural approach would be to develop a scoring system whereby metrics designed to represent system performance and system-planning goals could be weighed against metrics designed to represent facility performance, first and foremost V/C ratios, but potentially other facility-oriented metrics related to mobility, reliability and safety. Taken to its logical outcome, such a multi-objective multi-metric scoring system would require a set of weights and/or threshold values that would produce a composite score or rating. If this ideal scoring system were to yield a net detrimental rating, actions would need to be taken to mitigate the projected decline in composite performance.

4.1 IMPORTANT CAVEATS

Three cautionary limitations should be considered in determining whether and how to use certain metrics in an evaluation process: (1) the problem of unbounded metrics; (2) the problem of linkages between a particular metric and other system elements (which may or may not be measured as part of an evaluation process); and (3) assignment of causality to outcomes.

The problem of unbounded metrics is most intuitively characterized by the assumption that "more is always better," which ignores the existence of diminishing marginal returns (benefits), or even the possibility of negative net benefits occurring. For example, provision of bike infrastructure such as bike-lane striping is generally assumed to be a positive attribute. Thus, an agency could propose striping miles-and-miles of bike lanes and claim this as a mitigating factor in a plan amendment projected to worsen V/C ratios on local facilities. In this instance, the presumption would be that more bike lanes would reduce auto trips and provide a safer bicycling environment; however, this metric provides no information on either of these purported outcomes. Mere provision of bike lanes does not guarantee a fixed, proportionate response in bike ridership, nor does it say anything about latent demand for bicycling or what proportions of trips would be diverted from autos, transit and walk modes. Moreover, there would be diminishing returns to striping bike lanes, particularly in areas where demand is likely to be low. Information on existing and potential demand would be necessary to determine the true effects of bike-lane striping. If a more thorough analysis revealed that most of the gains in bike ridership were likely to come at the expense of transit patronage rather than auto usage, there could actually be net negative benefits. Mode diversions and safety effects from the provision of bike lanes would need to be assessed separately. The same would be true for other metrics in which it is assumed that more is better, including freeway lane miles with ITS, total freeway lanes miles, and transit supply. Thus, metrics related to the provision of infrastructure capacity are insufficient measures of the real outcomes of interest, even though they might be an input to the calculation.

The linkage problem is one in which given metrics are inextricably tied to other processes and system elements, as is the case with transit-oriented development. These processes and elements could include the presence or absence of complementary land uses and transportation system elements, as well as socioeconomic and market factors. Some of the metrics found in Table 3.1 include land use mix, population and employment density, accessibility to destinations, accessibility to transit, street network connectivity, and bike and pedestrian network circuitousness. Each of these metrics is individually assumed to have a positive effect on auto travel reduction, and a greater amount of each is assumed to result in a greater reduction. Thus, they are also subject to the more-is-better way of thinking. There is also a concern that rates of trip reduction commonly ascribed in the literature to these individual factors were estimated under conditions in which there were strong complementary forces at work.

The degree to which, say, greater densities result in a reduction in auto travel also depends on the provision of attractive alternatives, both in terms of destinations and travel modes. For example, a city could propose re-zoning to accommodate a 20-story high-rise office tower with ground-floor retail in a suburban location that is not well-served by transit, claiming an offsetting density credit. Without the support of enhanced transit options, however, this type of development would not lead to a reduction in auto trips compared with lower-density development, quite the opposite in fact.

Similarly, mixed-use residential and commercial development may not provide much in the way of trip reduction if residents are unlikely to work or shop nearby or if the development is likely to attract many trips from elsewhere, all of which will depend on the type of retail, resident incomes, auto ownership levels, and the attractiveness of competing destinations. Further, a large residential-commercial mixed use development is more likely to be a significant regional attractor in a smaller city where its commercial component faces less competition, while the same development would likely have a more beneficial impact on local auto traffic in a larger metropolitan area where its market area is more localized.

The point of discussing the linkages problem is that certain metrics may represent necessary but insufficient conditions for claiming offsetting mobility credits. Indeed, given the complexity of the land use and transportation relationships under consideration, it would seem that any of the metrics listed in Table 3.1 under the land use category might prove to be an imprecise predictor of auto travel reduction across varied circumstances. Instead, it is recommended that metrics related to the travel-behavior-related outcomes desired from land use changes be measured directly, such as changes to auto trip-length distributions and shifts to non-auto modes.

The causality assignment problem is closely related to the linkage problem. A prime example of this would be metrics such as accessibility to employment or population (e.g., *Cervero 2005*), weighted by an impedance function of mode-specific travel times or by composite costs (i.e., log-sums). This is also an unbounded measure in which more is usually assumed to be better. Mathematically, an increase in accessibility can result from reduced travel costs or an increase in attractions (e.g., number of jobs); however, it tends to work out that an increase in attractors will have a larger effect on accessibility scores than a change in travel costs. Thus, a plan amendment could show an improvement in accessibility even if it would result in slightly greater travel times across multiple modes, just because more attractors have been added. This occurs because the marginal impact of each new attractor unit (e.g., job) is greater than the marginal impact of that job on travel costs. The job is counted in the attraction scores of every TAZ, whereas the trips produced by that job are diffused across the network and modes. This kind of ambiguity may be avoided when accessibility metrics are related to defined locations in which the magnitude of attractiveness is held constant while travel costs to reach these destinations is allowed to vary (e.g., *Reiff and Gregor 2005*).

Another example of mistaken causality relates to reliability, in which a lower score for certain metrics is usually assumed to be better. When a particular highway facility routinely reaches a saturation level, then by definition this can actually make the facility seem more reliable than under lower-demand driving conditions. That is, it can become reliably slow moving, and an improvement in reliability metrics, such as the coefficient of variation and the buffer index (which normalize travel time variability by average travel times) can mask real problems. Thus, a plan amendment that would put more traffic on an already saturated facility could actually show an improvement in these reliability scores compared with a baseline case, even though the V/C ratio would worsen. Under certain ranges of input values, metrics such as these that can provide misleading indicators of system or facility performance and therefore may be less reliable indicators of truly beneficial outcomes. Other metrics, however, such as the planning time index (which normalizes the 95th percentile travel time by free-flow times) are likely to provide a more stable measure and should be preferred on this basis.

4.2 NEED FOR MODELING

One implication of the limitations discussed above is that supplemental performance metrics should reflect outcomes to traveler behavior, rather than concomitant conditions commonly associated with certain patterns of travel behavior. Secondly, there are important linkages between land use and transportation supply and demand, and these linkages conspire to change travel behavior. Thus, predicting travel behavior changes due to plan amendments requires careful consideration of known linkages. Network-based urban travel demand models offer the only obvious tool that can account for such complexity systematically and consistently to produce outcomes of interest for comparison with V/C ratios.

The third theme discussed in Section 4.1, that some metrics can produce ambiguous results under certain conditions, should serve to guide selection of outcome metrics by favoring those metrics that offer stable, unambiguous interpretations. Simulations using a travel demand model can help to identify which metrics provide consistent and stable interpretations.

Lastly, a distinction needs to be made between using a travel demand model to explore effects and trade-offs among supplemental performance metrics, and using such a model to support regulatory decisions. The present project is oriented toward the former objective. Hypothetically, while the latter objective is potentially achievable, it would require further consideration of issues related to the standardization of model structures and modeling protocols. Consideration would also need to be given to the treatment of local circumstances where a transportation demand model does not exist.

4.3 FACILITY UTILIZATION AND NETWORK EFFICIENCY

Efficient utilization of transportation facilities, with respect to both baseline and projected conditions, should also be part of the discussion of supplemental metrics. All else being equal, a plan, project or policy that promotes efficient utilization of existing assets, be they highway, transit or non-motorized facilities, should be viewed favorably and could offset to some degree the negative view of high roadway V/C ratios. The way this might occur in a plan amendment context would be a situation in which there is area-wide congestion and the proposed change would shift traffic patterns such that roadway V/C ratios closest to the subject site are made a little worse, while V/C ratios in nearby congested parts of the network are improved. If total network travel time is made better in the aggregate compared with the base case, then a plan amendment would lead to an efficiency improvement if it promotes more consistent utilization of existing assets. From a least-cost planning perspective this may be interpreted as load balancing across facilities.

By focusing only on locations where V/C worsens while ignoring locations where V/C has improved, plan amendment evaluations may not recognize changes that yield net benefits to the system as a whole. Ideally, a network-wide efficiency metric would document net performance changes for both state and local transportation facilities. Systematic network-based travel demand modeling would be needed to predict the underlying shifts in travel patterns, which are ultimately expressed by the metric of total network vehicle travel time.

Network efficiency evaluation could be extended to a multi-modal framework by measuring changes in total network travel time across all modes. From a least-cost planning perspective, this approach would consider load balancing across modes. The key here would be to determine whether a projected outcome will result in a more efficient multi-modal utilization pattern, and the most direct way to measure that would be changes in person hours of travel.

5.0 CONCLUSION

This review has identified a set of transportation performance metrics that could potentially supplement ODOT's OHP mobility standards. A brief appraisal of the metrics has been provided, focusing mainly on reported evidence of the empirical relationship between these metrics and V/C, the current mobility standards metric. More general considerations related to the use of the supplemental metrics in evaluating facility and system performance are also discussed. Subsequent work will include selection of supplemental metrics for further analysis using a travel demand model.

Several general conclusions can be drawn from this review. First, the literature shows that there has been a substantial commitment to transportation performance measurement at the state and federal levels in the United States. The list of metrics used or suggested is extensive, covering a diverse range of performance dimensions. Yet, there is also evidence that performance measures are often not directly or clearly related to outcomes that are important to transportation policy makers and the public. Thus, transportation performance measures have sometimes been found failing with respect to accountability. In the present case, V/C represents the outcome of interest and it will be necessary to clearly establish empirical relationships to this outcome for given metrics to serve as supplements. Apart from serving stakeholder accountability, clear empirical linkages between V/C and supplemental metrics is needed to ensure legal defensibility of ODOT decisions under the TPR.

Second, in selecting V/C to represent the OHP's mobility standards, ODOT evaluated a number of metrics (including some covered in this review) against such criteria as consistency, data availability, forecastability, transparency/understandability, modal neutrality, and complementarily with other OHP policies. It also anticipated a need for flexibility. Generally, the metrics included in the present review have the ability to reinforce the performance of V/C against these evaluation criteria. The metrics' most useful contribution, however, may be in facilitating greater flexibility in implementing the OHP mobility policy. This seems particularly evident with respect to the potential contributions of the land use, urban design, and alternative mode metrics, for which empirical evidence of mobility outcomes is fairly strong and for which modeling opportunities appear promising.

This literature review has focused on supplemental metrics that could potentially serve OHP Policy 1F (*Highway Mobility Standards*). In selected instances, the metrics also relate to other OHP policies, including Policy 1A (*State Highway Classification System*), Policy 1B (*Land Use and Transportation*), Policy 1C (*State Highway Freight System*), and Policy 1G (*Major Improvements*). Thus, the usefulness of the supplemental metrics presented in this review will, in part, depend on their contributions to various OHP policies. For example, reliability metrics may provide important information in assessing the effects of given actions on Policy 1C.

One of the potential benefits of the use of supplemental metrics in implementing the plan amendment provisions of the TPR will lie in their ability to serve as a bridge linking Policy 1F and other OHP policies. This bridging role can be realized by gaining a better understanding of the functional relationships among metrics. Thus, an important purpose of subsequent modeling activity in this project will be to examine and document these functional relationships. Such effort should be distinguished from the need to identify performance metrics that specifically address each OHP policy. This latter need has been the focus of previous work (*Reiff and Gregor 2005*), which identified a large inventory of possible metrics and analyzed a select subset.

Lastly, returning to Brown's (*1996*) observation that the most successful performance measurement systems limit their attention to a "vital few" indicators, a case could likely be made for the need to maintain an extensive portfolio of metrics to supplement V/C. However, it should be a goal to make the size of the portfolio as small as possible. Maintaining a limited number of supplemental metrics would help to ensure that the resulting performance measurement system would still reasonably satisfy the criteria that previously favored V/C as the preferred metric, and would also help to avoid a "trivial many" outcome.

6.0 REFERENCES

American Public Transit Association (APTA). 2009. *2009 Public Transportation Fact Book, 60th Edition.* Washington, DC: author.

Balducci, P. and J. Stowers. 2008. *NCHRP Synthesis 378: State Highway Cost Allocation Studies.* Washington, DC: National Cooperative Highway Research Program, Transportation Research Board of the National Academies.

Bertini, R. 2005a. Congestion and its extent. In Levinson, D. and K. Krizek (eds.). *Access to Destinations: Rethinking the Transportation Future of our Region.* London, UK: Elsevier.

Bertini, R. 2005b. You are the traffic jam: An examination of congestion measures. Paper presented at the 85th Annual Meeting of the Transportation Research Board. Washington, D.C. Accessed at http://www.its.pdx.edu/pdf/congestion_trb.pdf on August 10, 2010.

Bhat, C., Handy, S., Kockelman, K., Mahmassani, H., Weston, L., Gopal, A., and I. Srour. 2002. *Development of an Urban Accessibility Index: Summary Report*. Project Summary Report 4938-S. Austin, TX: Center for Transportation Research, University of Texas. Accessed at http://www.ce.utexas.edu/prof/bhat/REPORTS/4938_S.pdf on August 22, 2010.

Brown, M. 1996. *Keeping Score: Using the Right Metrics to Drive World Class Performance.* New York, NY: Quality Resources.

Cambridge Systematics. 1998. *NCHRP Report 399: Multimodal Corridor and Capacity Analysis Manual.* Washington, DC: National Cooperative Highway Research Program, Transportation Research Board of the National Academies.

Cambridge Systematics. 2000. *NCHRP Report 446: A Guidebook for Performance-Based Transportation Planning.* Washington, DC: National Cooperative Highway Research Program, Transportation Research Board of the National Academies.

Cambridge Systematics, High Street Consulting Group, TransTec Management, Spy Pond Partners, and Ross and Associates. 2009. *Performance Measurement Framework for Highway Capacity Decision Making.* SHRP 2 Report S2-CO2-RR. Washington, DC: The Second Strategic Highway Research Program, Transportation Research Board of the National Academies. Accessed at http://onlinepubs.trb.org/onlinepubs/shrp2/shrp2_S2-C02-RR.pdf on August 10, 2010.

Cambridge Systematics, Texas Transportation Institute, University of Washington, and Dowling Associates. 2006. *NCHRP Web-Only Document 97: Guide to Effective Freeway Performance Measurement: Final Report and Guidebook.* Washington, DC: National Cooperative Highway

Research Program, Transportation Research Board of the National Academies. Accessed at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w97.pdf on August 10, 2010.

Capital District Transportation Committee. 2007. *The Metropolitan Congestion Management Process*. Accessed at http://www.cdtcmpo.org/rtp2030/materials/cm-doc.pdf on November19, 2010.

Carson, J., Mannering, F., Legg, B., Nee, J. and D. Nam. 1999. Are incident management programs effective? Findings from Washington state. *Transportation Research Record 1683,* pp. 8-13.

Cervero, R. 2005. *Accessible Cities and Regions: A Framework for Sustainable Transport and Urbanism in the 21st Century.* Berkeley, CA: Center for Future Urban Transport, Institute of Transportation Studies, University of California. Accessed at http://repositories.cdlib.org/its/future_urban_transport/vwp-2005-3 on August 10, 2010.

Cervero, R. 2002. Induced travel demand: Research design, empirical evidence, and normative policies. *Journal of Planning Literature,* 17, pp. 3-20.

Cervero, R. and G. Arrington. 2008. Vehicle trip reduction impacts of transit-oriented housing. *Journal of Public Transportation,* 11 (3), pp. 1-17.

Cervero, R. and J. Murakami. 2010. Effects of built environments on vehicles miles traveled: Evidence from 370 U.S. urbanized areas. *Environment and Planning A,* 42, pp. 400-418.

Chapman, J. and L. Frank. 2004. *Integrating Travel Behavior and Urban Form Data to Address Transportation and Air Quality Problems in Atlanta.* Final Report. Atlanta, GA: Georgia Department of Transportation.

Chin, S., Franzese, O., Greene, D., Hwang, H. and R. Gibson. 2002. *Temporary Losses of Highway Capacity and Impacts on Performance.* Report No. ORNL/TM-2002/3. Oak Ridge TN: Oak Ridge National Laboratory.

City of Portland. 1998. *Portland Pedestrian Master Plan*. Portland, OR: Pedestrian Transportation Program, Office of Transportation, author. Accessed at http://www.portlandonline.com/shared/cfm/image.cfm?id=90244 on August 10, 2010.

Cortright, B. 2008. *TPR, Rezoning and Traffic Impact Analysis.* Presentation at the Northwest Transportation Conference, Corvallis, OR.

Dailey, D. 2006. The Use of Weather Data to Predict Non-recurring Traffic Congestion. Seattle, WA: Washington State Transportation Center (TRAC), University of Washington. Accessed at http://www.wsdot.wa.gov/research/reports/fullreports/655.1.pdf on November 1, 2010.

Dickerson, A., Pierson, J. and R. Vickerman. 1998. *Road Accidents and Traffic Flows: An Econometric Investigation*. Canterbury, UK: Department of Economics, Keynes College, University of Kent at Canterbury. Accessed at ftp://ftp.ukc.ac.uk/pub/ejr/RePEc/ukc/ukcedp/9809.pdf on August 20, 2010.

Dill, J. 2004. Measuring network connectivity for bicycling and walking. Paper presented at the 83rd Annual Meeting of the Transportation Research Board. Washington, DC: author.

Dueker, K., Strathman, J. and M. Bianco. 1998. *TCRP Report 40: Strategies to Attract Auto Users to Public Transportation.* Washington, DC: Transit Cooperative Research Program, Transportation Research Board of the National Academies.

Evans, J., Pratt, R., Texas Transportation Institute, Parsons Brinckerhoff Quade & Douglas, Cambridge Systematics, Kuzmyak, J., SG Associates, Gallop Corporation, McCollom Management Consulting, Levinson, H. and K.T. Analytics. 2004. *TCRP Report 95: Traveler Response to Transportation System Changes. Chapter 9 – Transit Scheduling and Frequency.* Washington, DC: Transit Cooperative Research Program, Transportation Research Board of the National Academies.

Ewing, R. and R. Cervero. 2010. Travel and the built environment: A meta-analysis. *Journal of the American Planning Association,* 76, pp. 265-294.

Federal Highway Administration (FHWA). 2008. *Highways and Climate Change*. Chapter 2: Opportunities for linking transportation planning and climate change. Washington, DC: U.S. Department of Transportation, author. Accessed at http://www.fhwa.dot.gov/hep/climatechange/chapter_two.htm on August 10, 2010.

Federal Highway Administration (FHWA). 2007. *How to Use Operations Objectives in the MTP*. Washington, DC: U.S. Department of Transportation, author. Accessed at http://ops.fhwa.dot.gov/publications/moguidebook/chap_4.htm on August 10, 2010.

Federal Highway Administration (FHWA). 2005. *Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation.* Washington, DC: U.S. Department of Transportation, author. Accessed at http://ops.fhwa.dot.goV/Congestion_report/chapter5.htm on August 10, 2010.

Federal Highway Administration (FHWA). 1999. *Guidebook on Method to Estimate Non-Motorized Travel: Supporting Documentation*. Publication NO. FHWA-RD-98-166. Washington, DC: U.S. Department of Transportation, author. Accessed at http://www.tfhrc.gov/safety/pedbike/vol2/sec2.14.htm on August 10, 2010.

Flanigan, E. and M. Howard. 2008. *An Interim Guidebook on the Congestion Management Process in Metropolitan Transportation Planning.* Washington, DC: Federal Highway Administration, U.S. Department of Transportation. Accessed at http://ops.fhwa.dot.gov/publications/cmpguidebook/ on August 10, 2010.

Florida Department of Community Affairs (FDCA). 2007. *Transportation Concurrency: Best Practices Guide.* Tallahassee, FL: author. Accessed at http://www.dca.state.fl.us/fdcp/dcp/publications/Files/TCBP.pdf on August 10, 2010.

Florida Department of Transportation (FDOT). 2009. *2009 Quality/Level of Service Handbook.* Tallahassee, Florida: author. Accessed at http://www.dot.state.fl.us/planning/systems/sm/los/pdfs/2009FDOTQLOS_Handbook.pdf on August 10, 2010.

Florida Department of Transportation (FDOT). No date. *Florida Transportation Indicators.* Tallahassee, FL: Author. Accessed at http://www.floridatransportationindicators.org/index.php?chart=6d on August 10, 2010.

Frank, L. and G. Pivo. 1994. Impacts of mixed use and density on utilization of three modes of travel: Single-occupant vehicle, transit, and walking. *Transportation Research Record 1466,* pp. 63-70.

Furth, P. Hemily, B., Muller, T. and J. Strathman. 2006. *TCRP Report 113: Using Archived AVL-APC Data to Improve Transit Performance and Management.* Washington, DC: Transit Cooperative Research Program, Transportation Research Board of the National Academies.

Georgia Department of Transportation (GDOT). No date. *Transportation Enhancement (TE) Program*. Atlanta, GA: author. Accessed at http://www.dca.state.ga.us/intra_nonpub/Toolkit/Guides/TEprgrms.pdf on August 10, 2010.

Golob, T., Recker, W. and V. Alverez. 2004. Freeway safety as a function of traffic flow. *Accident Analysis and Prevention,* 36, pp. 933-946.

Gordon, P., Kumar, A. and H. Richardson. 1989. The influence of metropolitan spatial structure on commuting time. *Journal of Urban Economics,* 26, pp. 138-151.

Greene, D. 1998. Why CAFÉ worked. *Energy Policy,* 26, pp. 595-613.

Gregor, B. 2009. *Analysis of Congestion and Travel Trends Reported in the 2009 Urban Mobility Study Report.* Salem, OR: Transportation Planning Analysis Unit, Oregon Department of Transportation.

Gregor, B. 2004. *Statewide Congestion Overview for Oregon.* Salem, OR: Transportation Planning Analysis Unit, Oregon Department of Transportation. Accessed at http://www.oregon.gov/ODOT/TD/TP/docs/tpauCM/overview0204.pdf?ga=t on November 1, 2010.

Hallenbeck, M., Ishimaru, J., and J. Nee. 2003. *Measurement of Recurring versus Non-recurring Congestion*. Report prepared for Washington State Transportation Commission. Seattle, WA: Washington State Transportation Center (TRAC), University of Washington.

Accessed at http://www.wsdot.wa.gov/research/reports/fullreports/568.2.pdf on August 10, 2010.

Handy, S., Boarnet, M., Ewing, R. and R. Killingsworth. 2002. How the built environment affects physical activity: views from urban planning. *American Journal of Preventive Medicine*, 23(2S), pp. 64-73.

Hedel, R. and C. Vance. 2007. Impact of urban form on automobile travel: Disentangling causation from correlation. Paper presented at the 86 Annual Meeting of the Transportation Research Board, Washington, DC.

Hess P., Moudon A., and M. Logsdon. 2001. Measuring land use patterns. *Transportation Research Record* 1780, pp. 17-24.

Institute of Transportation Engineers (ITE). 2003. *Trip Generation.* Washington, DC: author.

Jones, C. 2007. *Talking Freight.* PowerPoint presentation. Washington, DC: Federal Highway Administration, U.S. Department of Transportation. Accessed at www.fhwa.dot.gov/download/hep/talkingfreight11_21_07cj.ppt on August 10, 2010.

Kain, J. 1994. Impacts of congestion pricing on transit and carpool demand and supply. In Transportation Research Board, *Special Report 242: Curbing Gridlock – Peak Period Fees to Relieve Traffic Congestion, Volume 2.* Washington DC: Transportation Research Board of the National Academies.

Klop, J. and E. Guderian. 2008. *Linking of Mobility Performance Measures to Resource Allocation: Survey of State DOTs and MPOs.* Report No. CDOT-2008-13. Denver, CO: Research Branch, Colorado Department of Transportation. Accessed at http://www.coloradodot.info/programs/research/pdfs/2008/resourceallocation.pdf on August 10, 2010.

Kuzmyak, J., Evans, J. and R. Pratt. 2010. *TCRP Report 95: Traveler Response to Transportation System Changes. Chapter 19 – Employer and Institutional TDM Strategies.* Washington, DC: Transit Cooperative Research Program, Transportation Research Board of the National Academies.

Kuzmyak, J., Weinberger, R., Pratt, R. and H. Levinson. 2003. *TCRP Report 95: Traveler Response to Transportation System Changes. Chapter 18 – Parking Management and Supply.* Washington, DC: Transit Cooperative Research Program, Transportation Research Board of the National Academies.

MacDonald, D., Yew, C., Arnold, R., Baxter, J., Halvorson, R., Kassof, H., Meyer, M., Philmus, K., Price, T., Rose, D., Walton, C. and W. White. 2004. *Transportation Performance Measures in Australia, Canada, Japan, and New Zealand.* Report No. FHWA-PL-05-001. Washington, DC: Federal Highway Administration, U.S. Department of Transportation, and American

Association of State Highway and Transportation Officials. Accessed at http://international.fhwa.dot.gov/performance/04transperfmeasure.pdf on August 10, 2010.

Mannering, F. 1989. Poisson analysis of commuter flexibility in changing routes and departure times. *Transportation Research-B*, 23B, pp. 53-60.

McMullen, B. and C. Monsere. 2010. *Freight Performance Measures: Approach Analysis.* Report SPR 664; OTREC-RR-10-04. Salem, OR: Research Section, Oregon Department of Transportation. Accessed at http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/2010/Freight_Performance_Measures.pdf on November 1, 2010.

New Jersey Transportation Planning Authority (NJTPA). No date. *North Jersey Strategy Evaluation.* Newark, NJ: Author. Accessed at www.njtpa.org/planning/strat_eval/strat_eval.html on August 10, 2010.

National Cooperative Highway Research Program (NCHRP). 2007. *Research Results Digest 312: Guide to Effective Freeway Performance Measurement.* Washington, DC: Transportation Research Board of the National Academies, author.

National Transportation Operations Coalition (NTOC). 2005. *Performance Measures Initiative Final Report.* Washington, DC: author. Accessed at http://www.ntoctalks.com/ntoc/ntoc_final_report.pdf on August 10, 2010.

Needle, J. and R. Cobb. 1997. *Synthesis of Transit Practice 21: Improving Transit Security.* Washington, DC: Transit Cooperative Research Program, Transportation Research Board of the National Academies.

Oak Ridge National Laboratory (ORNL). 2010. *Transportation Energy Data Book: Edition 29.* Oak Ridge TN: Center for Transportation Analysis, Energy and Transportation Science Division, author.

Oregon Department of Transportation (ODOT). 2009. *Oregon Highway Plan Mobility Guidelines.* Salem, OR: author. Accessed at http://www.oregon.gov/ODOT/TD/TP/docs/orhwyplan/Mobility.pdf on August 10, 2010.

Oregon Department of Transportation (ODOT). 2008. *Development Review Guidelines*. Salem, OR: author. Accessed at http://www.oregon.gov/ODOT/TD/TP/DRG.shtml on August 20, 2010.

Oregon Department of Transportation (ODOT). 2006. *Interchange Area Management Plan Guidelines*. Salem, OR: Planning and Implementation Unit, Transportation Planning Section, author. Accessed at http://www.oregon.gov/ODOT/TD/TP/docs/publications/iampGuidelines.pdf on August 20, 2010.

Oregon Department of Transportation (ODOT). 2004. *Application of Oregon Highway Plan Mobility Standards*. Salem, Oregon: author. Accessed at http://www.oregon.gov/ODOT/TD/TP/docs/TAPM/vcRatio.pdf on August 10, 2010.

Oregon Department of Transportation (ODOT). 1999. *Oregon Highway Plan.* Salem, OR: author. Accessed at http://www.oregon.gov/ODOT/TD/TP/orhwyplan.shtml on August 10, 2010.

Oregon Department of Transportation (ODOT). 1998. *Report on 1998 Draft Highway Plan Level of Service Policy: Evaluation of Alternative Performance Measures and Recommendations for Policy Changes.* Salem, OR: Transportation Planning Analysis Unit, author.

Oregon Department of Transportation (ODOT). No date. *Oregon Truck Road Use Electronics Pilot Project (TRUE).* Salem, OR: author. Accessed at http://www.oregon.gov/ODOT/HWY/OIPP/TRUE.shtml on August 10, 2010.

Potts, J. 2002. *TCRP Synthesis 45: Customer-Focused Transit.* Washington, DC: Transit Cooperative Research Program, Transportation Research Board of the National Academies.

Pucher, J., Dill, J. and S. Handy. 2010. Infrastructure programs, and policies to increase bicycling: An international review. *Preventive Medicine,* 50, pp. S106-S125.

Quade, E. 1971. *A History of Cost-Effectiveness.* Paper No. P-4557. Santa Monica, CA: Rand Corporation. Accessed at http://www.rand.org/pubs/papers/2006/P4557.pdf on August 10, 2010.

Reiff, B. and B. Gregor. 2005. *Transportation Planning Performance Measures.* Final Report SPR 357. Salem, OR: Research Unit, Oregon Department of Transportation. Accessed at http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/PlanningPerformanceMeasures.pdf on November 1, 2010.

Research and Innovative Technology Administration (RITA). 2004. *Using Person Throughput Per Hour as a Performance Measure of Specific Portions of the Freeway System.* Washington, DC: U.S. Department of Transportation, author. Accessed at http://www.itsdeployment.its.dot.gov/Results.asp?ID=1019&rpt=A&filter=1&Year=2004 on August 10, 2010.

Sacramento Regional Transit. 2008. *FY 09- Key Performance Report*. Sacramento, CA: author. Accessed at http://www.sacrt.com/documents/KPR908.pdf on August 10, 2010.

Schrank, D. and T. Lomax. 2009. *2009 Urban Mobility Report*. College Station TX: Texas Transportation Institute, Texas A&M University. Accessed at http://tti.tamu.edu/documents/mobility_report_2009_wappx.pdf on August 20, 2010.

Small, K. 1982. The scheduling of consumer activities: Work trips. *American Economic Review*, 72, pp. 467-479.

Stecher, B., Camm, F., Damberg, C., Hamilton, L., Mullen, K., Nelson, C., Sorenson, P., Wachs, M., Yoh, A., Zellman, G. and K. Leuschner. 2010. *Toward a Culture of Consequences: Performance-Based Accountability Systems for Public Services.* Santa Monica, CA: Rand Corporation. Accessed at http://www.rand.org/pubs/monographs/2010/RAND_MG1019.pdf on August 22, 2010.

Strathman, J. and K. Dueker. 1996. Transit service, parking charges, and mode choice for the journey-to-work: An analysis of the 1990 NPTS. *Journal of Public Transportation,* 1, pp. 13-38.

Strathman, J., K. Dueker, T. Kimpel, R. Gerhart, K. Turner and S. Callas. 1999. Automated bus dispatching, operations control, and service reliability: Baseline analysis. *Transportation Research Record 1666,* pp. 28-36.

Strathman, J. and J Hopper. 1993. Empirical analysis of bus transit on-time performance. *Transportation Research –A,* 27A, pp. 93-100.

Strathman, J., Kimpel, T., Broach, J., Wachana, P., Coffel, K., Callas, S., Elliott, B. and Elmore-Yalch, R. 2008. *TCRP Report 126: Leveraging ITS Data for Transit Market Research: A Practitioner's Guidebook.* Washington, DC: Transit Cooperative Research Program, Transportation Research Board of the National Academies.

Texas Department of Transportation. 2001. *Traffic Data and Analysis Manual*. Manual 2001-1, Chapter 2.3: Travel demand modeling process. Austin, TX: author. Accessed at http://onlinemanuals.txdot.gov/txdotmanuals/tda/travel_demand_modeling_process.htm on August 10, 2010.

Transportation Research Board (TRB). 2002. *Special Report 264: The Congestion Mitigation and Air Quality Improvement Program: Assessing 10 Years of Experience.* Washington, DC: author.

Transportation Research Board (TRB). 2000. *Highway Capacity Manual*. Washington, DC: Transportation Research Board of the National Academies, author.

Turnbull, K., Pratt, R., Evans, J. and H. Levinson. 2004. *TCRP Report 95: Traveler Response to Transportation System Changes. Chapter 3 – Park and Ride/Pool.* Washington, DC: Transportation Research Board of the National Academies.

U.S. Department of Transportation. 2002. *DOT Performance Plan – FY2003 and Performance Report – FY2001. Appendix 1: Data Details.* Washington, DC: author. Accessed at http://www.dot.gov/performance/pdf/complete.pdf on August 10, 2010.

Virginia Department of Transportation. No date. *LOS Definitions Used in Traffic Impact Analysis*. Richmond, VA: author. Accessed at http://www.virginiadot.org/projects/resources/LOS-defined.pdf on August 10, 2010.

Wang, C., Quddus, M. and S. Ison. 2009. Impact of traffic congestion on road accidents: A spatial analysis of the M25 motorway in England. *Accident Analysis and Prevention,* 41, pp. 798-808.

Washington State Auditor's Office (WSAO). 2007. *Washington State Department of Transportation: Managing and Reducing Congestion in Puget Sound.* Performance Audit Report No. 1000006. Olympia, WA: author. Accessed at http://www.sao.wa.gov/auditreports/auditreportfiles/ar1000006.pdf on August 10, 2010.

Weiler, B. 2008. *Efficient Movement of Goods*. Jefferson City, MO: Missouri Department of Transportation. Accessed at http://www.modot.mo.gov/about/documents/Tracker_PDF_Jan08/Efficient11.pdf on August 10, 2010.

Willson, R. 1991. *Employer Parking Subsidies, Mode Choice, and Public Policy.* Unpublished Ph.D. dissertation. Los Angeles, CA: University of California.

Wray, J. 1998. *Policy for Applying LOS and V/C in the Transportation Development Process*. Columbus, OH: Ohio Department of Transportation, author. Accessed at http://www.dot.state.oh.us/policy/PoliciesandSOPs/Policies/322-002%20%28P%29.pdf on August 10, 2010.

Young, W., Thompson, R. and M. Taylor. 1991. A review of urban car parking models. *Transport Reviews*, 11, pp. 63-84.