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Accessing Information about Transportation Systems Management and Operations Performance Measurement

Prepared for:
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Prepared by:

Dr Aleksandar Stevanovic
(Florida Atlantic University)
Civil, Environmental & Geomatics Engineering
777 Glades Rd., Bldg # 36, Rm. 225
Boca Raton, Florida 33431.

Mr. Michael Pack
Mr. Mark Hallenbeck
(University of Washington)
Dr. Lily Elefteriodou

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Summary Page

The Final Report for NCHRP 20-07/Task 366: "Accessing Information about Transportation Systems Management and Operations Performance Measurement"

Project:	NCHRP 20-07/Task 366: Accessing Information about Transportation Systems Management and Operations Performance Measurement
Performing Agency:	Florida Atlantic University 777 Glades Road Boca Raton, FL 33431
Person Submitting Report:	Dr. Aleksandar Stevanovic
Report Written by:	Dr. Aleksandar Stevanovic, Florida Atlantic University Dr. Ali Soltani Sobh, Florida Atlantic University Mr. Michael Pack Mr. Mark Hallenbeck, University of Washington Dr. Lily Elefteriadou
Proposal Date:	December 15, 2014
Principal Investigator:	Aleksandar Stevanovic Florida Atlantic University Civil, Environmental & Geomatics Engineering 777 Glades Rd. Bldg. 36 Rm. 225 Boca Raton, FL 33431 (561) 297-3743 astevano@fau.edu
Administrative Officer:*	Miriam Campo, Director, Sponsored Programs Florida Atlantic University Division of Research, 777 Glades Road, ADM 10/Room 210A, Boca Raton, FL 33431 (561) 297-0853; campom@fau.edu
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Contents

Chapter 1 - Understanding the Problem

1.1 Introduction

In December 2014, the National Academies of Sciences (NAS) awarded to Florida Atlantic University (FAU) a research contract NCHRP 20-07/Task 366, under the National Cooperative Highway Research Program (NCHRP). Under this contract, the FAU research team and the subcontractors, working closely with the research panel developed a “Framework for Accessing Information about Transportation Systems Management and Operations Performance Measurement.” The research contract funded research activities for the period of February 12, 2015 to December 31, 2015. The research team for the NCHRP Project 20-07/Task includes Dr. Aleksandar Stevanovic (Florida Atlantic University), Mr. Michael Pack, Mr. Mark Hallenbeck (University of Washington) and Dr. Lily Elefteriadou.

This document, a draft of the final report, includes deliverables from the three Memorandums which have already been submitted. More precisely, this final draft contains the proposed Information Organization Framework (IOF)[1] with the embedded list of categories to classify/filter various performance measurements from the most relevant and most recent literature[2]. In addition, this final draft of the report describes the problems and opportunities for practitioner(s) who adopt the specific performance measurements according to federal rulemaking under MAP-21 legislation[3].

The goal of this provisional submittal is to allow the panel to serve as a resource to this project by assisting the research team in validating the proposed work structure and the depth of the contents. Moreover, successful completion of this project depends on the suggestions and comments from the panel and key stakeholders. For direct feedback, the research team will organize and coordinate a teleconference to present and discuss this technical report with the panel.

1.2 Research Background

Performance measurement and monitoring is the cornerstone of MAP-21’s highway program transformation towards an outcome-based transportation system. Various state departments of transportation (DOTs) work to improve the transportation system’s service to its users in order to contribute to the nation’s economy and get prepared for the provided federal guidelines and targets. State agencies have various perspectives on selecting and using performance measures. These differences may be especially visible when considering usefulness, selection of target values, and other operational aspect of performance management.

[1] This information organization framework is investigated in Memorandums 1 and 2
[2] The extensive literature review has been performed in Memorandums 1 and 2
[3] This task has been investigated in Memorandum 3

The Federal Highway Administration defines Transportation Systems Management and Operations (TSM&O) as "an integrated program to optimize the performance of existing multimodal infrastructure through implementation of systems, services, and projects to preserve capacity and improve the security, safety, and reliability of our transportation system." The program TSM&O actively manages multimodal transportation networks, and delivers positive safety and mobility outcomes based on performance measurements. With deteriorating infrastructure and fewer resources to build new roads it is critical to fully utilize existing road infrastructure. An assessment of how fully or efficiently something is being utilized is possible only if one measures the current level of utilization and compares this with the ultimate capacity/efficiency that can be achieved. TSM&O partners are public and private agencies united in the goal to make cost-effective decisions and leverage existing infrastructure.

At a time when legislation is transferring MAP-21's high-end goals into more specific directives, it is easy to become lost in the myriad studies which address measurement, monitoring, and management of system performance. With new types of measurement techniques, data, tools, and metrics being rolled out on a regular basis, it can be difficult for practitioners to know which measures are truly helpful, meaningful, and communicative.

For example, dozens of studies on TSM&O performance have been completed under National Cooperative Highway Research Program (NCHRP) alone. Other agencies such as DOTs, FHWA, FTA, etc. have funded numerous efforts on their own. While the information on some of these studies is accessible (through open access web portals), it is still very difficult to find appropriate, concise, and relevant information in a timely manner, especially given that many of these measures are used for internal purposes only. It is thus clear that practitioners could benefit from a comprehensive guidance on how and where to find the proper information. Such guidance should provide a user with information on how relevant certain measures are for a specific subject matter in which he/she is interested.

A limited foundation for such guidance already exists. The American Association of State Highway and Transportation Officials (AASHTO) have made some efforts in this area. The www.transportationops.org/ web portal (formally www.tsmoinfor.org/) is a starting point to find information about TSM&O-related studies and performance monitoring, measurement, and management. With its current filtering structure and brief profiles for each selected study, the www.transportationops.org/ web portal certainly represents one way to make the information from performance-management studies easily accessible and neatly presented. The TSM&O-related information in the previous www.tsmoinfor.org/ web portal is arranged in a systematic framework. This arrangement has been modified in the current www.transportationops.org/ web portal with some additional categories and subcategories as presented in Table 1.1. Based on the performance measures extracted from literature, the panel members recognizes to add Freight and Road Weather Management strategies to current TSM&O strategies. Below are a few suggested improvements that could enhance the framework:

1. ***Further categorization/filtering mechanisms, which will enable the end-user to identify, select, and review performance management studies even in a more comprehensive way than it is currently possible***,

2. ***Addition of numerous new studies, reports, and practices, which can significantly increase the amount of information available on the TSM&O web portal,***

3. ***Utilization of sources beyond literature and technical reports where TSM&O elements of success could be archived, such as videos, pictures, animations, etc. Therefore, the website could be designed or modified to archive information in different formats (multimedia repository) for completeness.***

Table 1.1: TSM&O Strategies

TSM&O Strategies
1- Access Management
2- Active Parking Management
3- Active Traffic Management
4- Adaptive Traffic Signal Technology
5- Bicycle and Pedestrian Management
6- Corridor and Arterial Traffic Management
7- Freeway Management
8- High Occupancy Vehicle (HOV) Lanes
9- Pricing/Toll Roads
10- Ramp Metering
11- Geometric Design
12- Traffic Signal Program Management
13- Signal Timing
14- Transit Operation
15- Transit Signal Priority
16- Travel Demand Management
17- Freight
18- Road Weather Management

This study addresses the dynamic nature of performance measurements and practices within the transportation industry. The highly fluid, highly variable, and highly customized nature of this industry can perpetuate confusion (e.g. performance measures with the same name derived in multiple ways), problems, and missed opportunities.

Each Agency often chooses which measure to report on based on available data sources and their ability to compute these measures. With MAP-21 requirements looming, many agencies are now attempting to standardize which measures they regularly report to help ensure that neighboring jurisdictions, states, etc. are all using similar terms—thus enabling more consistent reporting and enabling cross-Agency comparison. However, simply agreeing to report on the same type of measure may not be sufficient.

The way in which an Agency computes each of these measures (variations on formulas, variations on base inputs, etc.) can have significant consequences on both the resulting output and the overall meaning behind the measure. For example, the way in which Buffer Time Index (BTI) is calculated can result in completely different interpretations and meanings behind this misunderstood measure (see the detailed example below). These variations can lead to more complications and the misconception of an "apples-to-apples" comparison where none exists.

Therefore, it is necessary to summarize the current practices in developing and adopting performance measures around the country and to identify problems, opportunities, and consequences for practitioners' adoption of specific measures. Also, with new federal rules (created under MAP-21 legislation) arriving sometime in 2016 it is necessary to coordinate process and outcomes of this study with the MAP-21 legislative activities.

FHWA has already proposed the organization of many performance-related provisions within MAP–21 into six elements. The six elements related to MAP–21requirements are:

- ***National Goals***: Goals or program purpose established in MAP–21 to focus the Federal-aid highway program on specific areas of performance
- ***Measures***: Establishment of measures by FHWA to assess performance and condition in order to carry out performance-based Federal-aid highway programs
- ***Targets***: Establishment of targets by recipients of Federal-aid highway funding for each of the measures to document expectations of future performance
- ***Plans***: Development of strategic and/or tactical plans by recipients of Federal funding to identify strategies and investments that will address performance needs
- ***Reports***: Development of reports by recipients of Federal funding that would document progress toward the achievement of targets, including the effectiveness of Federal-aid highway investments
- ***Accountability***: Requirements developed by FHWA for recipients of Federal funding to use to achieve or make significant progress toward achieving targets established for performance

Under MAP-21, states are required to invest resources in projects to attain individual targets that will jointly make progress toward these national goals.

1.3 Research Objectives and Approaches

The objectives of this research are threefold:

Objective (a): To establish a framework for organizing information about research and practices for TSM&O performance measurement, and monitoring to assess the impacts of TSM&O strategies, concentrating on those aspects of TSM&O that are less well developed or most difficult to measure.

Approach: In order to accomplish this objective, the research team will develop a methodology to categorize existing performance measurement literature. The team will start from existing categories (also known as "Elements of Success" from the TSM&O Knowledge Transfer System (under the Document Library on www.tsmoinfor.org, recently changed to www.transportationops.org/). The existing categories will be reviewed, edited as necessary, and new categories will be suggested for addition. Also, the team will explore and propose other sources TSM&O information beyond literature and technical reports where elements of success could be archived, such as videos, pictures, animations, etc. For instance, the team might suggest a category of "expected benefits from TSM&O deployment" with subcategories listed under that primary heading. The team will work with the project panel members to identify which new categories should be included. To serve this purpose, the research team will create a comprehensive list of potential categories, which are currently not part of the "Elements of Success." For example, the team may investigate inclusion of traffic safety, transportation security, environmental factors, public transportation, and heavy vehicles. Subcategories of the existing "Elements of Success" will also be considered. For example, the team and panel might find beneficial to divide the Arterial Traffic Control Device Operations into signalized operations, stop-control operations, roundabouts, and innovative intersection operations (which can be further subdivided), and apply similar subdivisions elsewhere. The decision on how extensively to branch out with new subcategories will be based on: ***1. Literature review***, ***2. Judgment of the team members (e.g. how frequently is a search for performance measures of roundabouts needed)*** and ***3. Inputs from the panel***.

Special attention will be given to those categories, for which the performance measures are more difficult to report or are less frequently used. Library scientists at FAU, UMD, and UW will be consulted for additional guidance on basic categorization practices. Special attention will be given to developing an appropriate hierarchy of categorization and classification that is unambiguous, and large enough to encompass all necessary categories, yet small enough to ensure usability.

Objective (b): To facilitate practitioner access to such information by developing a guide to the most relevant recent literature (that is, selected print and web documents published within the past 5 to 7 years).

Approach: The research team will work with the research panel members, NCHRP, SHRP2, and TRB to identify the best way to integrate research outputs into a web platform that will be integrated with the existing TSM&O web platform (www.transportationops.org/). Modalities of integration will be coordinated with the National Operations Center of Excellence (NOCoE) to ensure that the research outputs from this project complement (in terms of format and context) material on the tsmoinfor.org platform.

Upon approval of the proposed web database framework, the research team will work with UMD development staff and www.TSM&Oinfo.org's maintenance staff to incorporate new structure. Regardless of the approach taken, special attention will be given to the usability and visual appeal of the website. UMD's User Experience (UX) and User Interface (UI) experts will craft multiple design alternatives for potential implementation. The ultimate goal will be to deploy a maintainable, easily updatable, and user-friendly resource of which the steering committee and users will be proud, able to use on a regular basis, and which will be easily marketable to practitioners with no training.

The web database will be populated with data from the current, relative studies and resources. The team will also attempt to make it possible to reference "coming soon" resources that are expected to be released in the near future. These data will include everything that the tsmoinfor.org website includes now [e.g. profile of a study which includes title, number, author, abstract, keywords (elements of success), and web link], plus additional elements which will make search and access of performance-measure-related studies easier and more meaningful.

Abstracts may need to be altered and/or summarized further to reduce ambiguity for practitioners, ensuring that users don't become frustrated with having to read copious amounts of abstracts and reference materials that are only tangentially related. The research team will provide multiple short abstracts (a paragraph or less with bullet points) to provide various perspectives/angles on the study. For example, if a study contains three keywords (elements of success): e.g. Performance measurement, Reliability, and Costs and Benefits, the research team will provide one general abstract/overview and three specific abstracts each of which summarize this study from a single perspective (e.g. one for performance measurement, one for reliability, and one for costs and benefits). Also, the research team will propose a way to attach 'keyword strength' of each keyword/category/element of success in the profile of each study. Equivalent to the strength of our cellular phone's signal or product ratings on Amazon, this 'keyword strength' will help practitioners to understand how much a certain study is really about a specific element of success/keyword. With such information, the users can focus their attention on the studies, which put more emphasis on certain subjects than the others did.

Objective (c): To describe the problems, opportunities, and consequences for practitioner(s) adoption of specific measures and setting targets for TSM&O performance management, with particular attention to federal rulemaking under MAP-21 legislation.

Approach: To accomplish this goal, the research team will reach out to leading performance measure implementers (specifically, those working with multiple states and multiple agencies) to evaluate the impacts of the methodologies and metrics. Concisely, in a shorter account of the problem and opportunities, the team envisions creating a series of tables, charts, and/or matrices that could serve as a quick-reference to practitioners.

Chapters 2, 3 and 4 relate to the objectives defined in (a), (b) and (c), respectively.

Chapter 2 - Information Organization Framework

This section of the final report describes how the information obtained from the literature search will be organized to make it easily accessible to users.

In the course of MAP-21's national performance goals transfer into specific mandates, there is a need to devise efficient and effective mechanisms for archiving, and accessing information pertinent to transportation systems performance measurement, monitoring, and management. Given the plethora of materials on performance management being added on a daily basis, it is too burdensome to identify proper information and consistent performance measures and targets specifically related to TSM&O. Since the achievement of MAP-21's performance goals will be gauged at the federal level, uniformity should be maintained in the adoption of measures and setting of targets among all state DOTs and other transportation agencies. In order to provide an efficient and uniform means for the agencies and practitioners to access concise and relevant information related to the topic of performance measurement for TSM&O, it is crucial to design a framework for accessing such information about performance measurement, monitoring, and management, exclusively tailored for MAP-21 requirements.

The purpose of this task is to develop a framework for the organization of information from the existing and new/future performance measurement studies and integration of such framework in the www.transportationops.org/ web portal, formerly www.tsmoinfor.org. The development of such a framework begins with the identification of primary classification categories and subcategories of several studies related to performance measurement, for efficient, uniform and meaningful access to information. There are several methods for creating primary classification categories and subcategories. The methods of classifying documents into categories fall under topic indexing methodologies. Topic indexing methods can generally be organized according the source of the terminology used to refer to a document's concepts and the number of topics assigned per document *(1)*. In the context of library science, topic indexing can be done using text categorization, term assignment, key-phrase extraction, terminology extraction, full-text indexing, key-phrase indexing and tagging. The descriptions of these items are briefly given in Table 2.1.

TABLE 2.1: Descriptions of Topic Indexing Methodologies *(Adopted from (1) with Modifications)*

Method	Alternative Name	Definition
Text categorization	Text classification	Very specific general categories, like Planning or Operations, are assigned from usually a small vocabulary in the context of performance measures.
Term assignment	Subject indexing	Main topics are expressed using terms from a large vocabulary, e.g. a thesaurus. The list of categories created in this Task 2, can serve as our thesaurus
Key-phrase extraction	Keyword extraction, Key term extraction	Main topics are expressed using the most prominent words and phrases in a document
Terminology extraction	Back-of-the-book (BOB) indexing	All domain relevant words and phrases are extracted from a document
Full-text indexing	Full indexing, Free-text indexing	All words and phrases, sometimes excluding stop-words, are extracted from a document
Key-phrase indexing	Full indexing, Free-text indexing	All words and phrases, sometimes excluding stop-words, are extracted from a document
Key-phrase indexing	Key-phrase assignment	A general term, which refers to both term assignment and key-phrase extraction
Tagging	Collaborative tagging, Social tagging, Auto-tagging, Automatic tagging	The user defines as many topics as desired. Any word or phrase can serve as a tag. Applies mainly to collaborative websites

The research team proposed categories to classify and filter various performance-measurement-related studies in order to enable easy and meaningful access of this information by TSM&O

practitioners. This proposed categorization framework can be used by practitioners, who are looking for assistance in selecting the proper performance measures to assess various TSM&O strategies. The framework methodology is based on the TSM&O's strategies, which is presented in Figure 2.1.

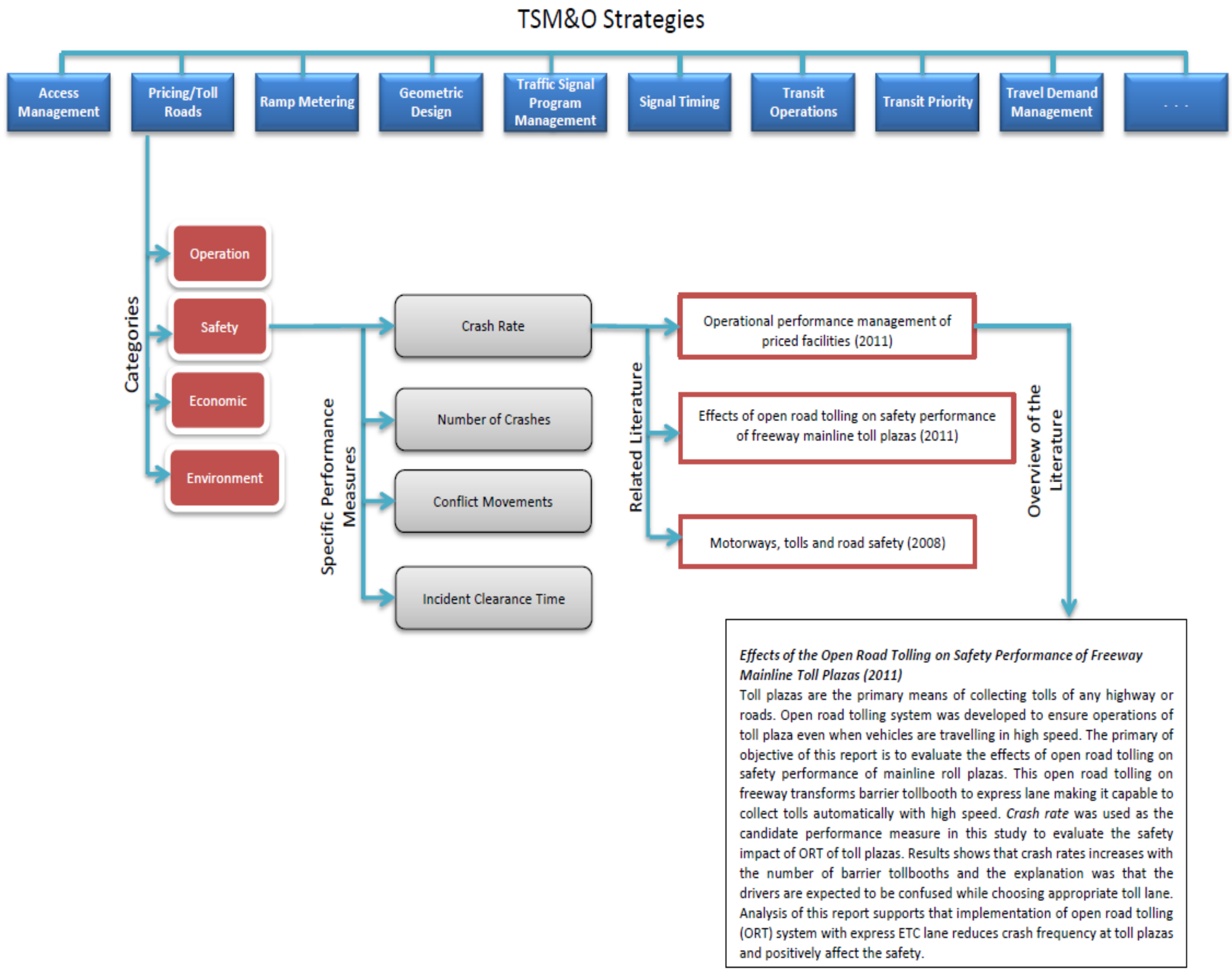

FIGURE 2.1: Organizational Framework for Retrieving Literature Summarize on Specific Performance Measure

For each of the presented TSM&O strategies the performance measures are introduced based on their appearance in various studies in the literature. The performance measures are grouped in following four categories:

- Operations
- Safety
- Economics
- Environment

Each individual specific performance measure is included in one or more of these four categories. For example, for Access Management as a TSM&O strategy, the assessment process can be conducted in terms of these four categories. In order to evaluate the effects of Access Management on traffic operation, various measures were found in the literature such as Travel Time, Speed, Delay, and Queue Length**.**

Considering that the specific objectives of this study are centered at catering for performance-related provisions within MAP–21, the identification of this classification categories and subcategories is limited to **text categorization, subject indexing and key-phrase extraction**. This is to ensure that when users search for a specific topic, the most relevant studies will appear rather having dozens of generalized documents.

For this task of the research project, a list of performance measures was developed from TSM&O studies performed under the NCHRP and SHRP2 programs, as well as under specific programmatic efforts by agencies such as FHWA.

The concept of this framework is based on the hierarchal filtering of the literature. The following describes how a user would access the information summarized in this study – in the first stage, the user would select a specific TSM&O strategy similar to how this task is performed on the www.transportationops.org/ web portal. After filtering by one of the specified strategies, an associated category for performance measures should be selected (e.g. Operations, Safety, Economics, and Environment).

In next step (e.g. within the web interface used for accessing this information), the specific performance measures that are used for different TSM&O strategies should be selected. In response to this selection of performance measures, various studies related to the selected performance measure (which have been used to evaluate that specific TSM&O strategy) are presented. The user is then presented with a brief description for each of the selected studies, from a particular perspective of the selected performance measure. Figure 2.1 shows part of the organization for the developed categories and sub-categories.

Chapter 3 - Integration of the Literature in IOF

The purpose of this task is to conduct a literature review of the available performance measurement studies, to be included in the tsmoinfor.org portal. The literature review includes documentation of current agency practices, system performance statistics, and DOTs' research and implementation activities.

Material from each of the reviewed studies was processed to produce a short study profile similar to the ones available on the tsmoinfor.org web portal (including links to electronic files and URL addresses). The research team reviewed most of the studies about various TSM&O strategies assessment.

The literature review presented in following section is consistent with the proposed performance measures categorization for various TSM&O strategies. For each TSM&O strategy, various performance measures (and brief literature reviews) are extracted and listed under categories of Operations, Safety, Economics, and Environment.

1 Access Management

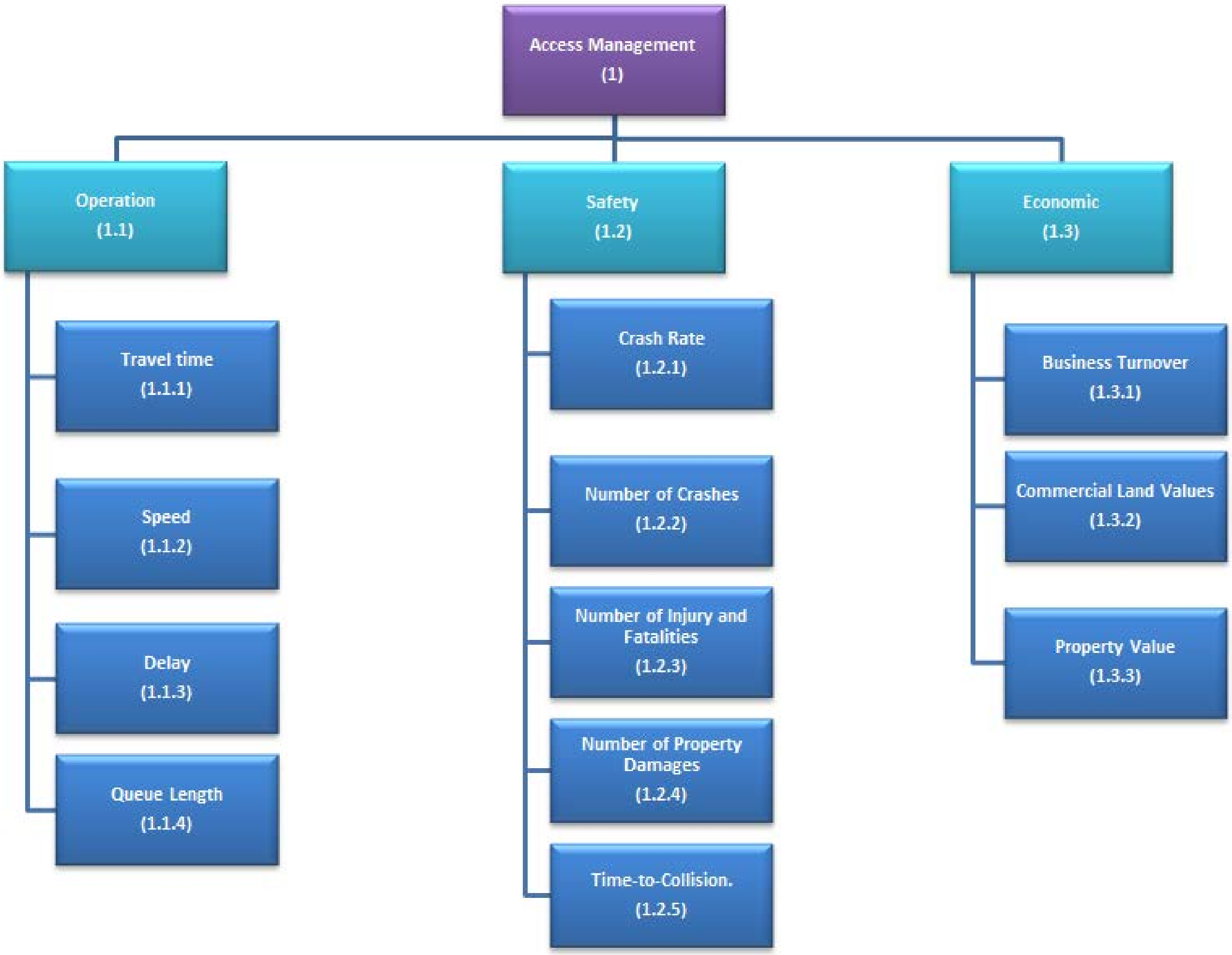

FIGURE 3.2: Access Management TSM&O strategy, categories and performance measures

1.1 Operations

1.1.1 Travel Time

1.1.2 Speed

1.1.3 Delay

1.1.4 Queue Length

- ***Impacts of Access Management Techniques (Gluck et al., 1999)***

(Travel time, Speed)

The NCHRP Report 420 on the *Impact of Access Management Techniques* developed a method to predict and analyze the effects of some selected access management techniques on traffic operation, using travel time and speed as performance measures. From several research projects and data collection efforts, this report concluded that traffic signal spacing was one of the most important access management techniques in regard to its effect on travel time. Travel time significantly increases for additional traffic signals per mile. For example, travel time is 16 percent higher in a segment with 4 signals per mile than a segment with 2 signals per mile. Another important access management strategy this report illustrated is un-signalized access spacing. Every access point per mile reduces speed by 0.25 mph, which results in a reduction of 10 mph when given 40 access points per mile. The report also concludes that the use of median treatment alternatives like separating left turning vehicles from through traffic by dedicated left turning lanes is also a useful technique to reduce travel time. A right turn from a driveway followed by a U-turn location also results in lower travel times on a busy road than a direct left turn exit.

- ***Access Management Performance Measures for Virginia: A Practical Approach for Public Accountability* (Connelly et al., 2010)**

(Travel time, Delay, Speed)

This report was conducted to improve the access management program of Virginia. Several appropriate reports were reviewed to establish potential and promising performance measures (PMs), which directly describe the traffic congestion experienced on highways. Recommendations were made at the end with some guidelines to summarize the PMs, including those which describe the influence of access management activities on traffic congestion.

The most important strategy this report recommends to reduce traffic congestion is the median treatment. According to this report, implementing strategic median openings with dedicated left turn lanes significantly reduces delay as it separates the left turning vehicles from the through traffic. Proper installation of traffic signals is another essential way to improve traffic congestion. Based on a survey, it was concluded that each additional traffic signal per mile considerably reduced the arterial speed. Spacing of intersections is another feature this report concentrated on regarding travel time. The free flow of traffic speed is reduced by 0.15 mph for each additional access point per mile, which dramatically decreases 5 to 10 mph travel speed for substandard driveway.

- ***Developing an Oregon Access Management Best Practices Manual* (Dixon et al., 2013)**

(Travel time, Speed, Delay)

This report reviews various research reports to address potential access management treatments and their associated performance measures. In addition to research studies, it includes different access management guidelines or policies developed by many state agencies. The influence of various access management strategies on traffic congestion was analyzed and summarized in this report. Travel time, Speed, and delay are performance measures used in this review to assess various strategies.

Median treatment is one of the common strategies to help channelize traffic flow conditions and consequently reduce vehicle conflicts. Several studies evaluating the effectiveness of median treatments indicated significant delay reductions resulting from this strategy. The strategic spacing of signalized intersections is another way to improve traffic operation. Based on the literature review included in this report, it was concluded that the spacing of traffic signals can directly influence operating speed and delay. Dense placement of driveways and street intersection access points also induce delay to the traffic stream. Strategies to manage un-signalized intersections and driveways help to lower traffic delay by decreasing the number of conflict movements. Another recommended strategy to enhance traffic operation is adding auxiliary lanes. The literature for this report demonstrates that the installation of left-turn lanes reduces delay by separating the left-turning vehicles from through traffic. The use of U-turns as an alternative to direct left-turns was considered as another strategy to diminish roadways travel time and delay.

- ***Cost and Benefits of Strategic Actuation of Limited Access Right-of-Way at Freeway Interchange Areas* (Kristine et al., 2004).**

(Delay, Queue length)

The Center for Urban Transportation Research (CUTR), under a grant from the Florida Department of Transportation (FDOT) examined the cost effectiveness of purchasing additional limited access right-of-way. One of the primaries advantageous of this strategy is increasing operational efficiency. The model of operation was simulated in CORSSIM. Two measures of effectiveness were used to evaluate the effects of the various degrees of access control on interchange operations. Those measures are: 1) Queue Length on the interchange off-ramp; and 2) Vehicle Hours of Delay for the entire network.

1.2 Safety

1.2.1 **Crash Rate** (Crash per million VMT)

1.2.2 Number of Crashes

1.2.3 Number of Injury and Fatalities

1.2.4 **Number of Property Damages** (Number of property damages only (PDO))

1.2.5 **Time-to-Collision** (Time takes for a vehicle to collide into another if they continue at the same speed without trying to avoid each other)

- ***Impacts of Access Management Techniques (Gluck et al., 1999).***

(Crash rate)

This report reviewed several literatures, analyzed, and summarized some priority access management techniques which impact crash per million VMT (crash rate) as roadway safety performance. The density of traffic signals in an area plays a direct role in crash rate. It was reported from several researches that as spacing of traffic signal decreases crash rate increases. Frequency of driveway and intersection is another potential factor which affects crash rate as crash increases significantly with each additional intersection. Alternative median strategies influence roadway safety to a moderate extent. Studies suggested that non-traversable medians results lowest crashes than undivided facilities and two-way-left turning lanes. Removing left turning vehicles from through traffic by a dedicated left lane reduces crash rates by roughly 50 percent. This study also summarizes that using U-turns as an alternative to direct left turns impact road safety positively as it results 20 percent crash reduction.

- ***Access Management Performance Measures for Virginia: A Practical Approach for Public Accountability*** **(Connelly et al., 2010).**

(Crash rate)

After widespread survey, key access management strategies this report suggests the following to improve safety: reduction of conflicts points, adequate distance between traffic signals, adequate distance between unsignalized access points, use of medians and two way left-turn lanes (TWLTLs), use of dedicated left turn lanes, restriction of median opening to appropriate locations, use of frontage road and supporting streets. In this research the crash rate, which is defined as number of crashes per million VMT, was used as safety indicator of different access management strategies.

- ***Developing an Oregon Access Management Best Practices Manual*** **(Dixon et al., 2013)**

(Crash rate)

In this report, several research on quantifying access management benefits on safety were summarized. This document introduced number of crashes per million VMT (crash rate) as a measurable criterion to evaluate access management. Common access management techniques and information about safety performance measures associated with were provided. The techniques proposed in this report include:

- Median Treatment Alternatives,
- Signalized Intersection Spacing,
- Unsignalized Intersection and Driveway Spacing,
- Auxiliary (Left-turn and Right-turn) Lane Installation,
- U-turns as Access Management Strategies, and
- Access Management at Roundabout and Interchanges.

- ***Cost and Benefits of Strategic Actuation of Limited Access Right-of-Way at Freeway Interchange Areas* (Kristine et al., 2004).**

(Injury, Fatality, Property damages)

Under a grant from Florida Department of Transportation, the Center for Urban Transportation Research conducted this research to assess the cost effectiveness of acquiring additional limited access right of way for controlling access in the functional area of interchanges. One of the potential benefits of this strategy is reduction of traffic crashes in freeway due to the traffic back-up causing lane blockage. To quantify the safety benefits, safety analysis was conducted for three different types of crashes, including Fatalities, Injuries, and Property damages.

- ***Identifying and quantifying operational and safety performance measures for access management: micro-simulation results* (Eisele and Toycen, 2005).**

(Time-to-Collision)

This research investigated performance measures that are applicable in evaluating access management strategies in term of surrogate safety measures. Microsimulation was performed on two corridors as case studies to obtain operational and safety information. In order to use microsimulation to evaluate safety impacts of access management, the safety surrogates were incorporated into VISSIM environment. In this study time-to-collision (the time it would take for a vehicle to collide into another if they continue at the same speed without trying to avoid each other) was used as safety measure.

1.3 Economics

1.3.1 Business Turnover

1.3.2 Commercial Land Values

1.3.3 Property Value

- ***Impacts of Access Management Techniques* (Gluck et al. 1999).**

(Property value)

In this report change in land use, and property value were identified as two measures for evaluating economic impact of median opening. Economic impact depends on developed, restricted or denied access with various alternatives of median opening. For example, if direct left turn is prohibited in some area, vehicles will travel to continuous pattern for established facility. This study also summarized that any establishment with the maximum number of left-turn entrances has the most economic benefits.

- ***Access Management Performance Measures for Virginia: A Practical Approach for Public Accountability*** **(Connelly et al., 2010)**.

(Business turnover, Commercial land value)

Access management is a strategy for improving highway operation and safety. Generally, access management has a positive impact on economic development at the national level. This report concludes that proper access management of interstate highway system has a good economic impact on the locality, since it increases the traffic flow and speed, and reduces the fatal crash rate. These factors have a neutral positive influence on land use, income, business turnover, and commercial land values. However, this report also suggests that access management may have a positive or negative economic effect on single business. Access management restricts accessibility to certain property, though it increases the volume of traffic passing that location, it may have a negative economic impact of that property. These outcomes compete to create both positive and negative economic effects.

- ***Developing an Oregon Access Management Best Practices Manual*** **(Dixon et al., 2013).**

(Property value)

Access management is frequently cited as systemic approach to improving safety and traffic operation. Occasionally, various strategies indirectly affect economic. This report summarized various literatures with regard to assessing the overall economic impacts of access management. Some strategies particularly relate to restrictive median and driveways will have effect on property values, as well as business access and sales. Historically, access management affects economically related points by changing the accessibility and exposure of potential visitors to the site. In some situations, access management adversely affects access to local business by restricting driveway frequency, configuration, or location. In this report, besides the overall economic impact of access management, economic implication of median alternatives and interchange constraints were analyzed.

2 Active Parking Management

FIGURE 3.3: Active Parking Management TSM&O strategy, categories and performance measures

2.1 Operations

2.1.1 Travel Time

2.1.2 Duration of Vehicle Trips

2.1.3 Number of Double Parking

2.1.4 Parking Space Availability (Percent of spaces occupied)

- ***The Active Transportation and Demand Management Program (ATDM): Lessons Learned* (Kuhn et al, 2013).**

(Travel time, Duration of vehicle trips, Number of double parking)

This information brief was performed by Federal Highway Administration. Active parking management system is a part of active transportation demand management. Its goal is to manage parking facilities to improve utilization of those facilities and to influence travel behavior along different steps of trip making decisions. The overall goal of active parking management is to maximize the nation's transportation investment by reducing congestion and improving safety. These strategies can reduce congestion in and around the parking facilities and foster public trust. In addition, active parking management system benefits the region by reducing pollution, encouraging using alternate routes, relieving congestion around commercial businesses, and helping improve access by emergency responders. The objective of implementing this strategy was to increase parking availability, reduce the number and duration of vehicle trips and reduce double parking.

- ***Contemporary Approaches to Parking Pricing: A Primer* (Kaufman et al., 2012).**

(Parking space availability)

This report by FHWA discusses parking management strategies and tools such as single space meters, multi space meters, in-car meters, pay by phone, license plate recognition technology, parking space sensors. The 194 million registered vehicles in the United States take up between 5,200 and 8,700 square miles of parking space. Accordingly, active parking management became a very important topic of research for last few decades. Pricing parking based on performance goals for the street or transportation system allows cities to better manage the parking supply. Parking space availability can be a simple measure to evaluate the performance of towns' parking management strategies. Parking spaces can be counted occasionally by conducting a manual count and supplementing such counts with meter-payment data. Parking experts generally agree that 10 to 20 percent (one or two spaces) of on-street parking per block should be vacant most of the time as a way to reduce cruising for parking. This primer also discusses the largest and most sophisticated performance parking program of United States, SFpark. This program includes 6,000 parking spaces in seven pilot districts. Also, SFpark uses a demand-responsive pricing to open up parking spaces on each block and ensure available spaces in city-owned garages.

3 Active Traffic Management

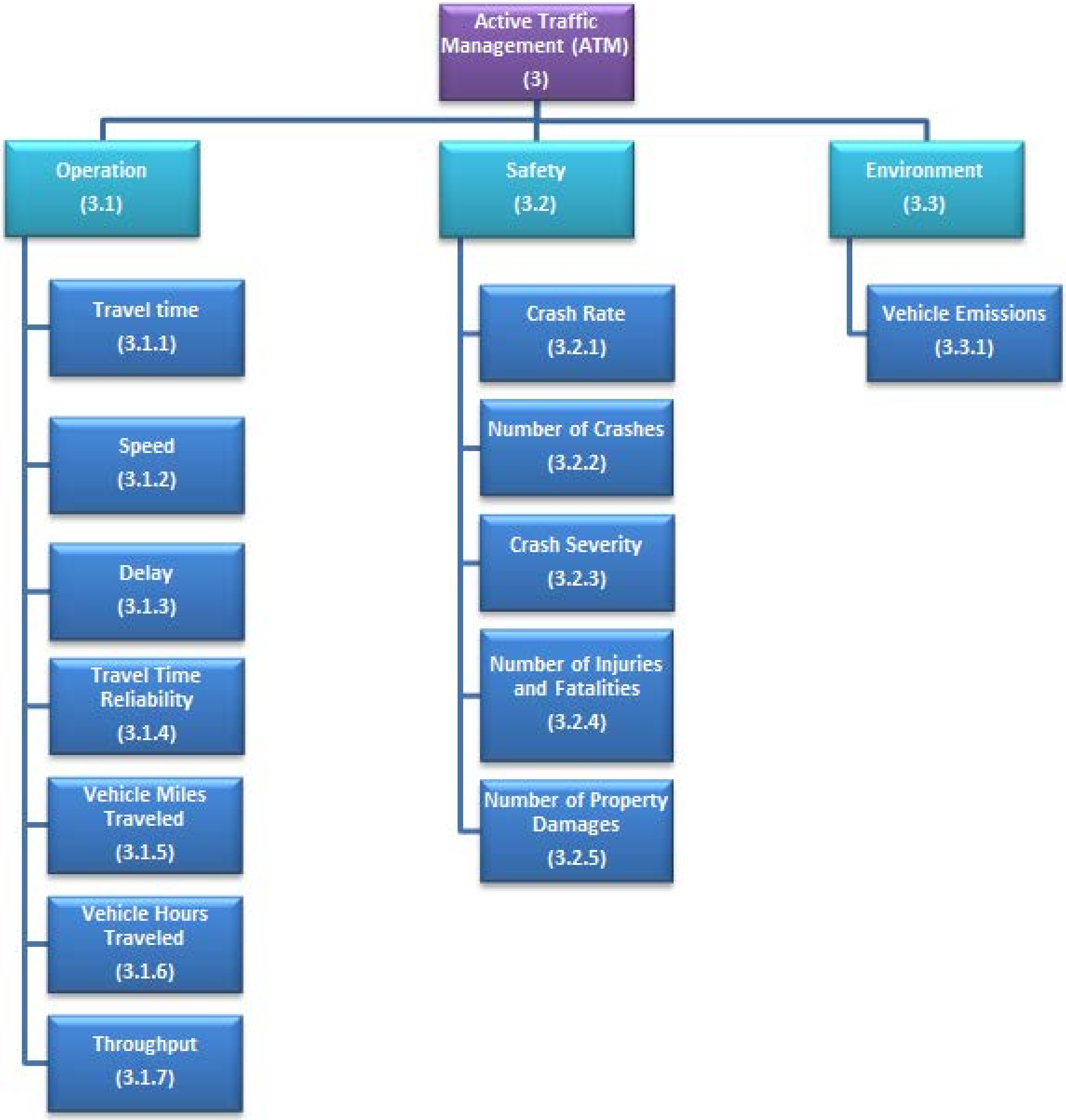

FIGURE 3.4: Active Traffic Management TSM&O strategy, categories and performance measures

3.1 Operations

3.1.1 Travel Time

3.1.2 Speed

3.1.3 Delay

3.1.4 Travel Time Reliability (Variation in travel time)

3.1.5 Vehicle Miles Traveled

3.1.6 Vehicle Hours Traveled

3.1.7 Throughput

- ***ODOT Region 1 Active Traffic Management Study Draft Methodology and Performance Measures memorandum*** **(Oregon Department of Transportation, 2015).**

(Travel time, Travel time reliability, Delay, Speed, Throughput)

In the Portland Metro Region, Active Traffic Management (ATM) operational strategies were developed to manage the freeway/highway facilities and improve effectiveness and efficiency of the transportation system. In this report the potential performance measures to evaluate the effectiveness of ATM strategies were reviewed. Congestion mitigation and reliability increment are preliminary objectives of ATM strategies. The reviewed performance measures in this report are travel time, travel time reliability, speed, throughput, delay, and congestion duration. Description and comments on each performance measures were provided in this study.

- ***Planning for Active Traffic Management in Virginia: International Best Practices and Implementation Strategies*** **(Fontaine and Miller, 2012).**

(Travel time, Travel time reliability, Throughput)

Managing a corridor is a presentation prepared for the SHRP2 project L36 Regional Operations Forums pilots. In this presentation, Active Traffic Management was considered as one of the policies and regulations intended to improve road safety and operation. Various ATM strategies and their examples in US were discussed in this presentation. In order to assess the impact of various strategies on traffic operation in this presentation, travel time, travel time reliability and throughput are mentioned as measure of performances.

- ***Implementing active traffic management strategies in the US*** **(Sisiopiku et al., 2009).**

(Travel time, Travel time reliability, Speed)

Active Traffic Management is defined as a set of strategies to mitigate traffic congestion. University Transportation Center for Alabama (UTCA) implemented this research on various ATM strategies. Speed harmonization, high occupancy vehicle lanes, junction control, and temporary shoulder lane use were considered as candidate strategies in this study. In order to assess impacts of various strategies on traffic operation, the value of travel time saving was used as performance measure. Travel time, speed, and travel time reliability are other indexes that used to evaluate ATM strategies.

- ***Active traffic management on road networks: a macroscopic approach*** **(Kurzhanskiy and Varaiya, 2010).**

(Actual travel time, Delay, Speed, Vehicle miles traveled (VMT), Vehicle hour traveled (VHT))

This study defined active traffic management (ATM) as a set of activities that manage the recurrent and non-recurrent traffic congestion to maximize the effectiveness and efficiency of road network. The open source macro simulation tool AURORA ROAD NETWORK MODELER was used to model and evaluate various ATM strategies. The devised strategies are demand management, incident management, providing traveler information, traffic flow control, variable speed limit, and using a signal timing plan. General link performance measures used in this study are: traffic speed, instantaneous travel time, actual travel time, vehicle miles traveled, vehicle hours traveled, delay, and productivity loss. For signalized arterial intersections, additional performance measures, such as delay per cycle, queue size, phase utilization, cycle failure, flow-to-capacity ratio and progression quality are applied.

3.2 Safety

3.2.1 **Crash Rate** (Crashes per million VMT)

3.2.2 Number of Crashes

3.2.3 **Crash Severity** (Sever crashes per million VMT)

3.2.4 Number of Injuries and Fatalities

3.2.5 Number of Property Damages

- ***Planning for Active Traffic Management in Virginia: International Best Practices and Implementation Strategies*** **(Fontaine and Miller, 2012).**

(Crash rate, Injury, Number of property damage)

Active Traffic Management (ATM) is a set of strategies to improve traffic operation efficiency. These strategies such as variable speed limits, queue warning system, and dynamic ramp metering are used to manage traffic flow to enhance capacity and safety. This study developed a guideline to incorporate various ATM strategies into the planning process. In order to side-by-side comparison of ATM projects, this report summarized effects of the ATM systems in safety. Variable speed limit (VSL), queue warning system, hard shoulder running, dynamic junction control, and dynamic ramp metering are strategies considered in this study. Crash rate, injury, and property damage are performance measures to assess safety impacts of various strategies.

- ***Implementing active traffic management strategies in the US*** **(Sisiopiku et al., 2009).**

(Number of crashes, Crash severity)

Road expansion limitations along with continued travel growth increase the needs of Active Traffic Management strategies (ATM). ATM includes various strategies which are used to maximize the efficiency of transportation facilities. University Transportation Center for Alabama provided this report as a summary of best practices as well as recommendations for advancing the research and implementation of ATM strategies. Speed harmonization, high occupancy vehicle lanes, junction control, and temporary shoulder lane use were introduced as strategies considered under ATM umbrella. Due to the safety importance in designing transportation facilities, it is considered as one of the ATM objective. The number of crashes as well as crash severity, which is defined as number of sever crashes per million VMT, are introduced as safety performance measures in this report. The study showed the significant safety enhancement as a result of different ATM strategies.

- ***ODOT Region 1 Active Traffic Management Study Draft Methodology and Performance Measures memorandum*** **(Oregon Department of Transportation, 2015).**

(Crash rate, Crash severity)

Due to the congestion growth in freeway corridors, the ODOT Region (1) is facing declining safety and reduced system reliability. In order to improve safety, research was conducted on Active Traffic Management strategy to manage the freeway/highway facilities in the Portland Metro Region. The ATM strategy in this study is relied on variable speed display, queue warning, and traveler information element. In order to determine the effectiveness of specific strategies, and to indicate how well the transportation system is meeting the objectives, some performance measures were used in this study. In this report crash rates are calculated to determine safety deficiencies and safety improvements of a particular corridor or location. Crash severity is another indicator that often measured by the number of injury crashes per month or per year of the corridor before and after the implementation of the proposed project.

3.3 Environment

3.3.1 Vehicle Emissions (Emission of hydrocarbons, carbon monoxide and nitrogen oxides)

- ***Implementing active traffic management strategies in the US*** **(Sisiopiku et al., 2009).**

(Vehicle emissions)

Implementing Active Traffic Management strategies provide too many opportunities for congestion reduction. University Transportation Center for Alabama conducted this research to assess the state of the practice for ATM strategies, as well as analyze potential operational benefits from implementing some of the strategies. The state of the practice was performed by reviewing four agencies current ATM projects. One of the strategies this study focused on was deployment of temporary shoulder lane use. In order to evaluate effect of shoulder lane utilization on environment, the amount of HC, carbon monoxide (CO), and nitrogen emitted vehicles were extracted from CORSSIM simulation results.

4 Adaptive Traffic Signal Technology

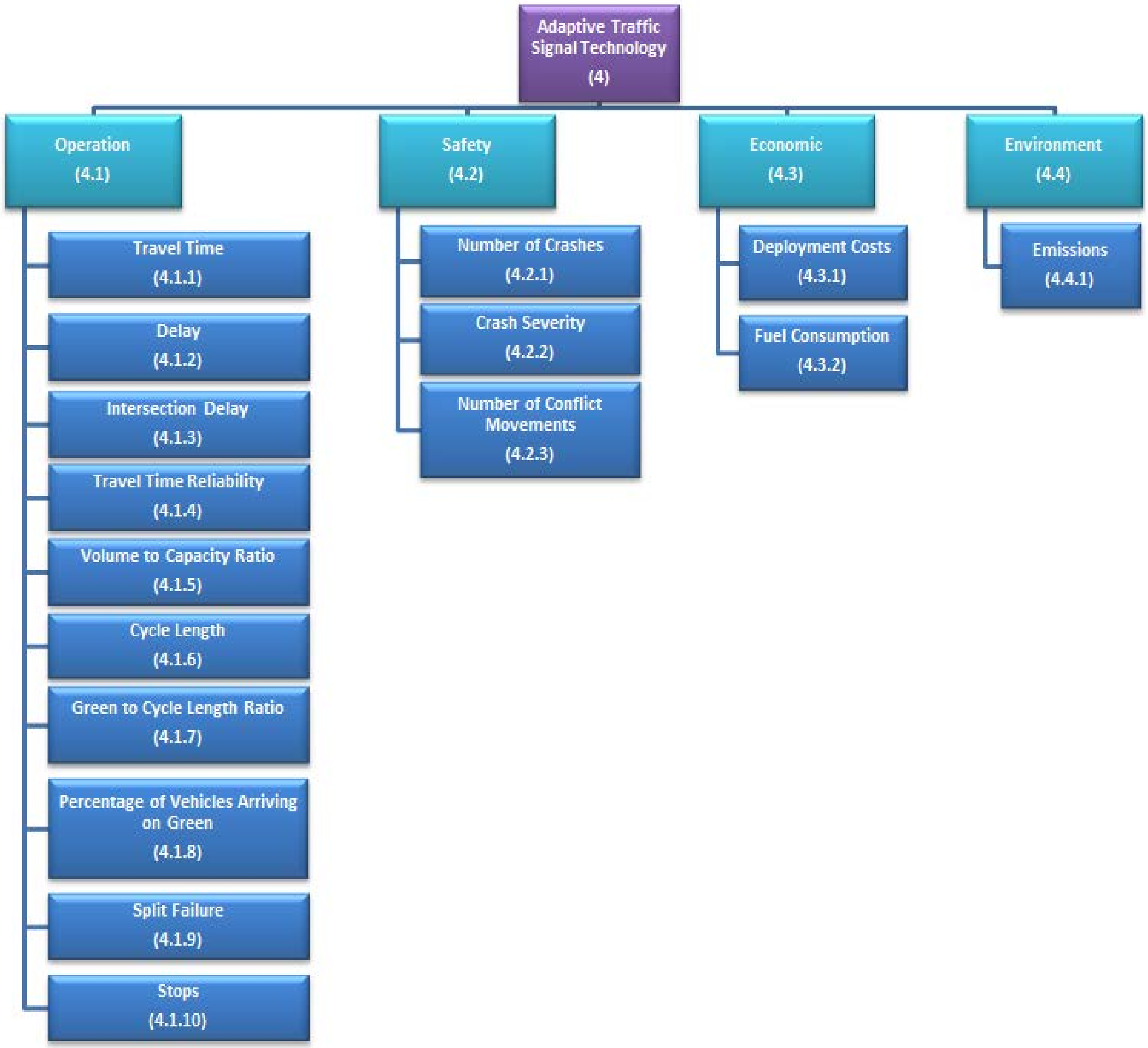

FIGURE 3.5: Adaptive Traffic Signal Technology TSM&O strategy, categories and performance measures

4.1 Operations

4.1.1 Travel Time

4.1.2 Delay

4.1.3 Intersection Delay

4.1.4 Travel Time Reliability (Variation in travel time)

4.1.5 Volume to Capacity Ratio

4.1.6 Cycle Length

4.1.7 Green to Cycle Length Ratio

4.1.8 Percentage of Vehicles Arriving on Green

4.1.9 Split Failure

4.1.10 Stops

- **Performance measures for adaptive signal control: case study of system-in-the-loop simulation (Day et al., 2012).**

(Delay, Cycle length, Green-to-cycle length ratio, Volume-to-Capacity ratio)

Adaptive signal control refers to technologies that adjust traffic signal timing based on current traffic demand data. This study used the VISSIM microsimulation package to evaluate adaptive signal control system. The methodology used to assess the adaptive signal control is termed "system-in-the-loop simulation" which links virtualized traffic controllers with real-world adaptive-control system. In this study, delay is the performance measure used to assess the effect of adaptive signal control on entire test network in different scenarios. Other alternative event-based performance measures are: cycle length, green-to-cycle length (g/c) ratio, volume-to-capacity (v/c) ration, and average delay

- ***Adaptive signal control system with online performance measure for a single intersection*** **(Liu et al., 2002).**

(Intersection delay, Percentage of vehicles arriving on green, Split failure)

The primary operational goal of a traffic control system is to minimize intersection delay by manipulating the traffic signal plans. Adaptive traffic control is a type of controller which conducts signal timing based on real time data. This paper proposed a system of adaptive signal control that utilizes real time delay estimation and on-line signal timing optimization algorithm. Intersection delay along with percentage of vehicles arriving on green, and split failure were used as performance measures. The performance of the method was estimated via simulation. The results demonstrate that control system could be an efficient method even under the application of a simple algorithm for adapting the signal timing plan. In addition, it was addressed that performance of the system can be improved by employing more complicated control logics.

- ***An overview of the usage of adaptive signal control system in the United States of America*** **(Zhao and Tian, 2012).**

(Travel time, Delay, Stops)

In this study, a comprehensive overview of adaptive traffic control systems is provided. The function and features of five major adaptive traffic control systems were reviewed, including SCOOT, SCATS, OPAC, RHODES, and ACS Lite. To evaluate the impact of various systems on operation efficiency, they were compared using travel time, delay, and stops as performance measures. The comparison results demonstrate that the ACS Lite does not provide cycle optimization, and it requires upstream detectors on coordinated approaches for offset optimization. SCOOT has the largest world-wide deployments, while SCATS has the largest U.S. deployments. Due to the short history of ACS Lite, it has a small number of deployments. However, the use of this system is expected to grow.

- ***Adaptive Signal Control Technology: Current Practice and Comparison*** **(De Jesus et al., 2011).**

(Travel time)

Adaptive signal control technology (ASCT) adjusts the timing plans of traffic signals based on prevailing traffic conditions and traffic demand. The paper on “Adaptive Signal Control Technology: Current Practice and Comparison” discusses the working principals, operational characteristics, benefits, and deployment cost of ASCTs. The most important measure of effectiveness the agencies were interested in improving was travel time. A related study at the University of Connecticut shows that weather adaptive signal control results in about 7% reduction in travel time and about 20% in average delay. In Houston, TX, an ACS-Lite system implemented in a Metropolitan area on 2.2 mile roadway length covering 8 intersections and the system has shown 5 to 25% improvement in arterial travel times.

- ***Adaptive Traffic Signal Control for Tarrytown Road in White Plains, New York*** **(Lardoux et al., 2014).**

(Travel time reliability)

The paper on “Adaptive Traffic Signal Control for Tarrytown Road in White Plains, New York” summarized the effect of implementing an adaptive traffic signal control system, SCATS (Sydney Coordinated Adaptive Traffic System) in nine intersections along Tarrytown Road in the City of White Plains, NY. SCATS uses a real time traffic adaptive approach to traffic control by measuring current traffic conditions and then adjusting the traffic signal cycle length, splits, and offsets. The use of adaptive traffic signal control technology has been proven to overall reduce travel time and travel time reliability along the corridor. A before and after study after the installation of the first 7 SCATS intersection shows that travel time was improved by 14% at the morning, 16% at midday and 30% at afternoon.

4.2 Safety

4.2.1 Number of Crashes

4.2.2 Crash Severity (Number of sever crashes per million VMT)

4.2.3 Number of Conflict Movements

- ***Safety Benefits of Implementing Adaptive Signal Control Technology: Survey Results* (Lodes and Benekohal, 2013).**

(Number of crashes, Crash severity)

Oakland County and a portion of Macomb and Wayne Counties of Michigan have deployed SCATS since 1992. It was found that SCATS is superior in several performance measures in terms of delay, traffic flow, and queue length. This study focuses on the safety effectiveness of SCATS system. In order to assess the impact of this type of adaptive signal control technology on safety, the number of crashes was used as performance measures. The evaluation was conducted through two folds: number of crash analysis before and after SCATS system installation, and safety performance comparison of SCATs controlled corridor with a similar pre-timed control corridor. The results of this study present that installing SCATS signal system decreases the severity of the crashes. In compare with pre-timed, the higher reduction in total crash per intersection and severity combined per intersection were observed in case of the SCATS system.

- ***Assessment of surrogate safety benefits of an adaptive traffic control system* (Stevanovic et al., 2011).**

(Number of conflict movements)

In this study framework is based on use of a microsimulation model connected to Sydney Coordinated Adaptive Traffic System (SCATS) to generate vehicular trajectories which are fed into a Surrogate Safety Assessment Model. SCAT and conventional time of day (TOD) control system were modeled as two operational designs in microsimulation environment. Surrogate Safety Assessment Model (SSAM) - software that calculates surrogate safety metrics based on conflicts between vehicular trajectories from traffic simulation outputs. The results demonstrate that SCATS generates fewer rear-end and total conflict due to its longer cycle lengths, while conventional TOD control generates fewer crossing and lane-changing conflicts.

4.3 Economics

4.3.1 Deployment Costs

4.3.2 Fuel Consumption

- ***An overview of the usage of adaptive signal control system in the United States of America* (Zhao and Tian, 2012).**

(Deployment costs)

The objective of this study is to review various adaptive traffic control systems. The function and features of five major adaptive traffic control systems were reviewed, including SCOOT, SCATS, OPAC, RHODES, and ACS Lite. In order to assess the economic impact of adaptive traffic control systems, the cost of deployment was introduced as performance measure. The comparison results demonstrate that ACS Lite requires minimal cost and less maintenance. SCOOT has the largest world-wide deployments, while SCATS has the largest U.S. deployments. Due to the short history of ACS Lite, it has small number of deployments. However, the use of this system is expected to grow.

- ***Adaptive Signal Control Technology: Current Practice and Comparison* (De Jesus et al., 2011).**

(Fuel consumption)

Adaptive signal control technology (ASCT) adjusts the timing plan of traffic signals based on prevailing traffic conditions and traffic demand. The paper on "Adaptive Signal Control Technology: Current Practice and Comparison" discusses the working principals, operative characteristics, benefits and deployment cost of ASCTs. Almost all case studies reviewed by this study illustrate several effective qualities of ASCT; one of them is fuel consumption. Three different case studies of three different ASCTs show a significant reduction in fuel consumption, from 1.21% to 61.54% in some cases. Fuel consumption reduction always directly results in monetary benefits. One specific ASCT system (InSync in Lee's Summit, MO) shows that it saves annually 34,250 gallons of fuel consumption; which represents a significant reduction of passengers' fuel cost.

- ***Intelligent Transportation Systems for Traffic Signal Control* (U.S. Department of Transportation, 2007).**

(Fuel Consumption)

Poor traffic signal timing accounts for an estimated 10 percent of all traffic delay, which results in about 300 million vehicle-hours on major US roadways. Intelligent transportation systems in traffic signal control include updated communication system, adaptive control systems, traffic responsive, real-time data collection and analysis, and maintenance management systems, which enable signal control systems to operate with greater efficiency. These systems reduce travel time and delay which indirectly results reduction in fuel consumption. Fuel efficient traffic signal management program in California showed an 8 percent reduction in fuel consumption. Improvement to 11-intersection arterial in St. Augustine, FL, showed significant reduction in arterial delay and travel time resulting 26,000 gallons fuel saving and a cost savings of $1.1 million. This report also discusses the potential benefit of U.S. traffic signal which will result fuel consumption reduction up to 10 percent, equal to a savings of 17 billion gallons of motor fuel reduction per year.

4.4 Environment

4.4.1 Emissions (Emission of GHG, carbon dioxide, hydrocarbons, nitrogen oxides, and volatile organic compounds)

- ***Smart Urban Signal Networks: Initial Application of the SURTRAC Adaptive Traffic Signal Control System*** **(Smith et al., 2013).**

(Emission)

The paper describes a pilot implementation and field test of a recently developed approach to real-time adaptive traffic signal control and performance of this adaptive system with pre-existing signal timings. The pilot system, called SURTRAC (Scalable Urban Traffic Control), follows the perspective of recent work in multi agent planning and implements a decentralized, schedule-driven approach to traffic signal control. One of the major measures quantified by this paper is emission. Emissions of carbon dioxide, hydrocarbons, carbon monoxide, nitrogen oxides and volatile organic compounds are calculated as a function of fuel consumption. From the perspective of improving the quality of the air, overall emissions are reduced by 21%, which implies reduction 2.253 metric tons of emission per day.

- ***Adaptive Traffic Signal Control for Tarrytown Road in White Plains, New York*** **(Lardoux et al., 2014).**

(Emission)

The report on "Adaptive Traffic Signal Control for Tarrytown Road in White Plains, New York" summarizes the effect of implementing an adaptive traffic signal control system, SCATS (Sydney Coordinated Adaptive Traffic System), in nine intersections along Tarrytown Road in the City of White Plains. SCATS uses a real time traffic adaptive approach to traffic control by measuring current traffic conditions and then adjusting the traffic signal cycle length, splits, and offsets. This strategy optimizes the flow by measuring the density of vehicles in each lane and reduces vehicles delay, which leads to greenhouse gas emission reduction without the cost of road widening. The reduction of emissions is directly attributed to more efficient traffic operations along the corridor. The expected reduction in fuel consumption is also closely correlates with reduction of GHG. Generally, burning one gallon of gasoline creates 19.57 pounds of CO_2.

5 Bicycle and Pedestrian Management

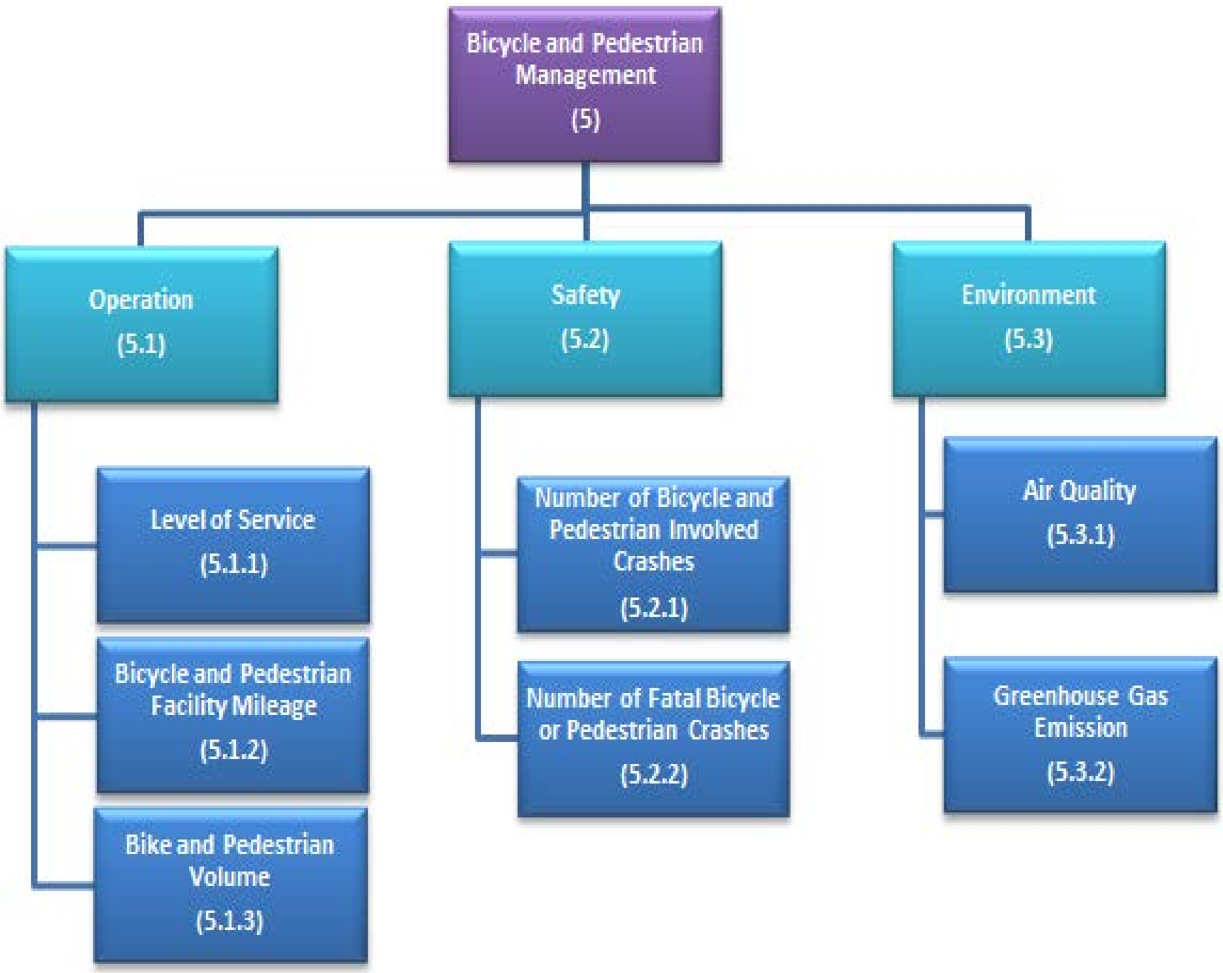

FIGURE 3.6: Bicycle and Pedestrian Management TSM&O strategy, categories and performance measures

5.1 Operations

5.1.1 Level of Service

5.1.2 Bicycle and Pedestrian Facility Mileage

5.1.3 Bike and Pedestrian Volume

- ***Bicycle and pedestrian level-of-service performance measures and standards for congestion management systems* (Dixon, 1996).**

(Level-of-Service)

This study was conducted by Gainesville Mobility Plan Prototype to develop a level-of-service (LOS) performance measure of bicycle and pedestrian facilities. The LOS performance measure demonstrates the share of the bicycle and pedestrian facilities in a transportation corridor. The introduced LOS in this study is based on a point system of 1 to 21 that rates LOS from A through F. The scoring system is sensitive to characteristics that may be mutually exclusive or inclusive to determine all possible combinations of points.

- **Quality and Level-of-Service Concepts (Highway Capacity Manual, 2010)**

(Level-of-Service)

HCM 2010 summarized the service measures as performance measures to evaluate the quality of various transportation mode services. For pedestrians and bicycles, the levels of service are used as performance measures. In this manual, the service measures of pedestrian and bicycle transportation are defined separately for various types of facility such as Freeways and Multilane highways, Two-lane-Highways, Urban Street Facility and Segments, and Urban Street Intersections. In each type of facility, various variables are incorporated to the system of LOS score model to determine LOS of pedestrian and Bicycle.

- ***Washington State Bike-Pedestrian Plan* (Washington Department of Transportation, 2008).**

(Bicycle and Pedestrian facility mileages)

Washington State has a number of existing laws, plans, policies, and programs intended to improve conditions for bicycling and walking. This study conducted research on plans for Washington State bicycle facilities and pedestrian walkaways consistent with Washington State Law (RCW47.06.100) and federal guidance. In this plan, the current bicycle and walking trends such as the status of infrastructure, safety statistics, programs, funding options, and performance measures were investigated. Moreover, to improve condition of bicycling and walking in Washington State, the ideas, guidance, and the implementation ways were recommended. Mobility is one of the bike-pedestrian strategic plans' goals. In this study, in order to measure the mobility of bicycle and pedestrian facilities, bicycle and pedestrian facility mileages were offered as performance measure.

- ***Oregon bicycle and pedestrian plan* (Cambridge Systematics, Inc., 2015)**

(Bicycle and Pedestrian volume)

This white paper, prepared for the Oregon DOT, describes and recommends several performance measures for consideration in the Oregon Bicycle and Pedestrian Plan. One of the important measures is pedestrian and bicycle volume, which can evaluate the performance of the bicycle and pedestrian plan. Pedestrian and bicycle volume models have been developed in a number of cities and states, and could be worth exploring as a means to develop estimates of pedestrian and bicycle trips. In the absence of a comprehensive measurement of pedestrian and bicycle volume, data from the Oregon Transportation Needs and Issues Survey were used to provide an indication of bicycling and walking utilization.

- ***Development of Performance Measures for Non-Motorized Dynamics* (Oh et al., 2013).**

(Bicycle and Pedestrian volume)

This report on "Development of Performance Measures for Non-Motorized Dynamics" recommends performance measures for non-motorized (pedestrian and bicyclists) traffic safety for Michigan cities. In modeling the non-motorized volume, pedestrian and bicyclist exposures are defined as the rate of pedestrian or bicyclist's contact with motorized traffic. Higher exposure results in more crashes involving non-motorized traffic. Even though pedestrian and bicycle volumes are essential for safety performance analysis and planning non-motorized facilities, there have been very limited efforts to collect and archive data, mainly due to lack of reliable and economic data collection means. In order to efficiently measure non-motorized facilities, there have been efforts to develop sensors for detecting, counting, and classifying pedestrians and bicycles. This study employed two approaches to pedestrian and bicycle volume data collection. The first was to collect 12-hour data at selected locations using automated pedestrian and bicycle sensors, and the second was to collect data manually for one hour at coverage locations.

5.2 Safety

5.2.1 Number of Bicycle and Pedestrian Involved Crashes

5.2.2 Number of Fatal Bicycle or Pedestrian Crashes

- ***Washington State Bike-Pedestrian Plan* (Washington Department of Transportation, 2008).**

(Number of bicycle and pedestrian involved crashes, Number of fatal bicycle or pedestrian crashes)

People interested in walking and biking need and want safe place to ride and walk. This study conducted a research on Washington State bicycle facilities and pedestrian walkaways plan consistent with Washington State Law (RCW47.06.100) and federal guidance. In this study, after analyzing the current trends in today bicycling and walking, recommendations were made to improve conditions for bicycling and walking and ways of implementation in Washington State.

One of the performance measures related to biking and walking is safety. This study reviewed various existing safety related benchmarks currently tracked by WSDOT and other agencies.

- ***Framework for Selection and Evaluation of Bicycle and Pedestrian Safety Projects in Virginia*** **(Natarajan et al., 2008).**

(Number of bicycle, pedestrian involved crashes)

Safety is an important issue for bicyclists and pedestrians. There are variety of funding programs provided by Virginia Department of Transportation (VDOT) for studies and projects to address the bicycle and pedestrian safety. In order to improve safety for bicyclists and pedestrians, VDOT's Bicycle and Pedestrian Safety (BPS) program was specifically created within VDOT's Highway Safety Improvement Program (HSIP). In this study, a comprehensive framework was developed to address various issues of BPS Program. The objective of this study was to identify hazardous locations and selecting countermeasures to eliminate the hazards. Bicycle and pedestrian safety hazards were identified based on the literature review and surveys. In this study, the number of crashes were applied as a performance measure to assess the effectiveness of hazards eliminating strategies.

5.3 Environment

5.3.1 Air Quality (Vehicle travel delay*Gallon of fuel/hour*Passenger car average emission of (CO+NOx+VOC))

5.3.2 Greenhouse Gas Emission

- ***Performance measures for bicycle and pedestrian investments*** **(Webber, 2014).**

(Air quality)

Measuring performance of bicycle modal and evaluating how policies and investments are contributing toward number of goals and performance metrics is critical. The goals largely focus on promoting personal mobility and reduction of congestion, emissions, and transportation costs. This study categorized the bicycle performance measures according to whether they are based on outputs or outcomes. Measures based on outputs are quantity of infrastructure, infrastructure rating, and accessibility. Whereas the outcome-based measures include economic development, public health, quality of life, mode shift congestion, and air quality.

- ***Washington State Bike-Pedestrian Plan*** **(Washington Department of Transportation, 2008).**

(Greenhouse gas emissions)

Higher fuel price and information about health and environment benefit increase the popularity of bicycling and walking. This study researched Washington State's bicycle facilities and pedestrian walkaways plan. In this plan, various recommendations and the ways of implementation were presented using analysis of current trends in bicycling and walking. The plan objective is to assess the statewide bicycle and pedestrian transportation need by conducting strategies such as improving connections, increasing coordination, and reducing traffic congestion. Walking and bicycling is a part of Washington State's strategy to improve public health and address climate change. In order to track, monitor, and report conditions for bicyclist and pedestrians, state agencies use benchmarks as performance measures. In this study, greenhouse gas emission was reported as an existing health and environment related performance measure.

6 Corridor and Arterial Traffic Management

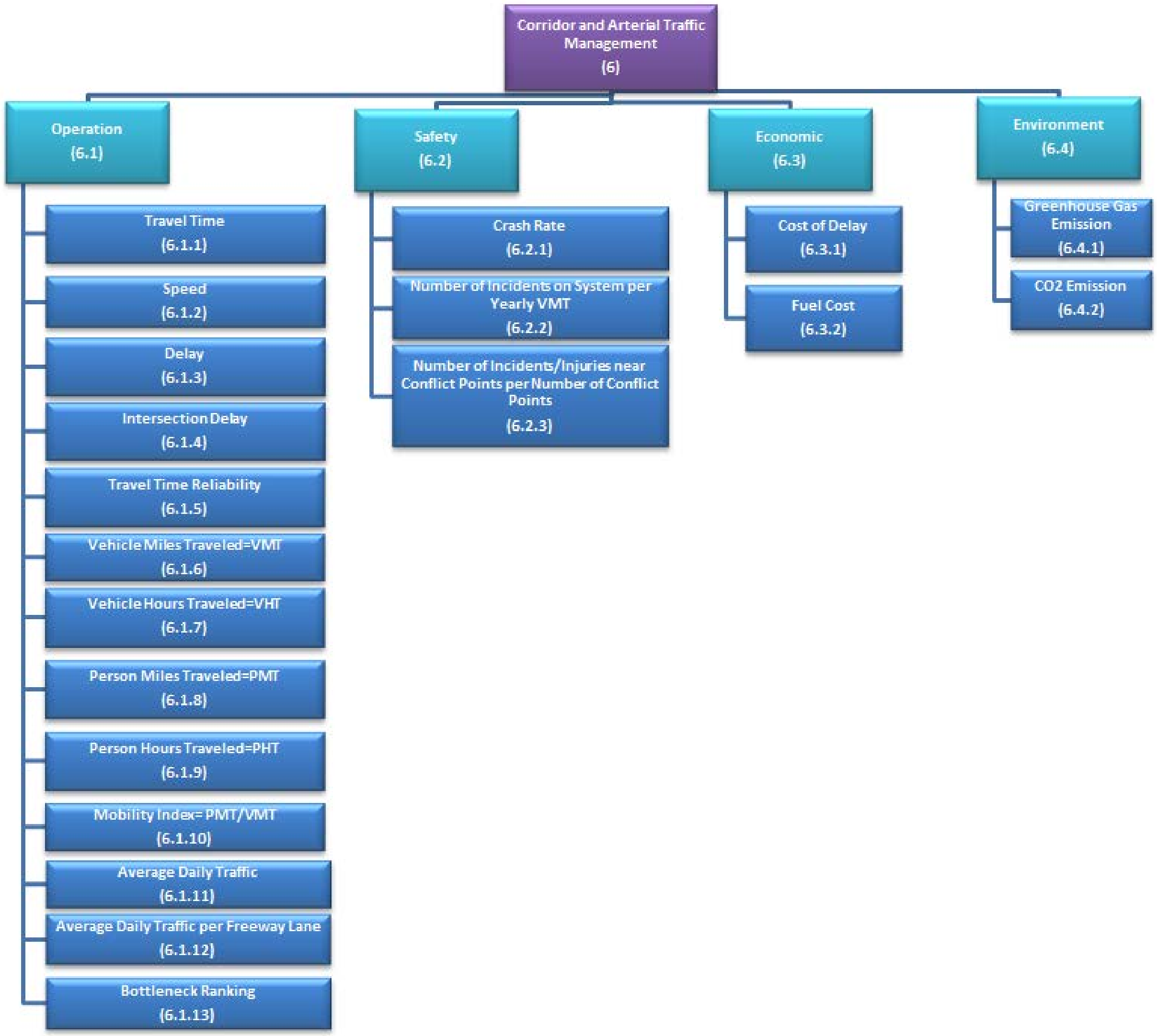

FIGURE 3.7: Corridor and Arterial Management TSM&O strategy, categories, and performance measures

6.1 Operations

6.1.1 Travel Time

6.1.2 Speed

6.1.3 Delay

6.1.4 Intersection Delay

6.1.5 Travel Time Reliability (Variation in daily travel time)

6.1.6 Vehicle Miles Traveled=VMT

6.1.7 Vehicle Hours Traveled=VHT

6.1.8 Person Miles Traveled=PMT

6.1.9 Person Hours Traveled=PHT

6.1.10 Mobility Index= PMT/VMT

6.1.11 Average Daily Traffic

6.1.12 Average Daily Traffic per Freeway Lane

6.1.13 Bottleneck Ranking

- ***Generating Performance Measures from Portland's Archived Advanced Traffic Management System Data* (Bertini et al., 2002).**

(Travel time, Average daily traffic, Speed, Vehicle miles traveled, person miles traveled, Intersection delay)

This paper established a set of performance measures using archived data in a freeway corridor in Portland, Oregon. This study illustrates that it is possible to evaluate the performance of services regarding measures like mobility, safety, economic development and environment using real data. Mobility of an arterial or corridor refers to free and easy movement of passengers from one place to another. Average Daily Traffic (ADT), Average Daily Traffic per Freeway Lane, Average Speed, Travel Time, Vehicle Miles Travelled, Person Miles Travelled, Mobility Index, Vehicle Hours Travelled, Persons Hours Travelled, Vehicle Miles Travelled by Congestion Level, Person Miles Travelled by Congestion Level, Percentage of VMT at a particular level of service, Percent of The Freeway Uncongested During Peak Hours, Number And Percent Of Lane-Miles Congested, Lost Time Due To Congestion, Demand Vs. Capacity, Percent of VMT Which Occurs On Facilities With Particular V/C Ratio, Delay Per Vehicle Miles Traveled, and Reserve Capacity are Mobility performance measures established in this research.

- ***Evaluation of Corridor Traffic Management and Planning Strategies That Use Microsimulation: A Case Study* (Liu and Jabari, 2008).**

(Travel time, Speed)

This study utilized microscopic simulation to evaluate corridor traffic management strategies emphasizing origin destination (O-D) calibration and peak spreading. Peak spreading is the process of reducing traffic congestion in the peak hour by increasing demand at time period immediately before and after the peak hours. This research shows that peak spreading strategy affects traffic operations in a positive way. In California SR-41 corridor, travel time and speed improvements ranged from 8% to 21% and vehicle released rate improved from 47% to 91%.

- ***Coordinated freeway and arterial operations handbook*** **(Urbanik et al., 2006).**

(Delay, Travel time reliability)

Coordinated Freeway and Arterial (CFA) Operations is the execution of strategies, technologies, and plans that can manage traffic jointly in freeway and arterial roads to improve mobility, reliability, and safety. *Coordinated Freeway and Arterial Operation Handbook* gives a guideline on how to efficiently manage traffic operations in freeway and arterial streets. Delay and travel time reliability were used as performance measures to assess impacts of these strategies. Four empirical studies in four different cities (Glasgow, Seattle, Anaheim and San Antonio) show that CFA operations play a positive role in reducing traffic congestion. For example, in Anaheim, CA, implementation of alternative corridor operation plans (signal timing plans, ramp metering plans, DMS messages and route diversion plans) during nonrecurring congestion reduces travel time up to 30%.

- ***Coordinated freeway and arterial operations handbook*** **(Urbanik et al., 2006).**

(Travel time, Intersection delay)

This paper portrays the usage of a performance measurement framework on a corridor in Los Angeles's South Bay to evaluate a major traffic signal coordination project on the corridor. The effect of fully actuated signals was measured on the operational performance of that arterial road and the performance measures considered were Intersection Control Delay and Travel Time. The results suggest that fully actuated signals reduced overall delay by 45%. This study also concludes that travel time is reduced at AM peak hours and midday while no significant change was observed at PM peak hours due to change in signal timing on that specific corridor.

- ***Traffic congestion and reliability: Trends and advanced strategies for congestion mitigation*** **(Federal Highway Administration, 2005).**

(Bottleneck ranking)

One of the measures used to identify the commonly congested roads is bottleneck ranking. Bottleneck ranking demonstrates how slow and dense congestion becomes at a bottleneck. The worst bottleneck identifications examine the possible positive effects that improving them could have on transportation system performance. The rank of bottleneck in a region can be a good measure to evaluate the efficiency of corridor and arterial traffic management strategies.

6.2 Safety

6.2.1 Crash Rate (Crashes per million VMT)

6.2.2 Number of Incidents on System per Yearly VMT

6.2.3 Number of Incidents/Injuries near Conflict Points per Number of Conflict Points

- ***Generating Performance Measures from Portland's Archived Advanced Traffic Management System Data* (Bertini et al., 2002).**

(Number of incidents on system per yearly VMT, Number of incidents/injuries near conflict points per number of conflict points)

Every agency associated with transportation planning aim to ensure a high level of mobility in the roadways while keeping the passengers safe, making safety a primary goal of transportation planning. This report on established several performance measures evaluates the safety issue of eastbound U26 corridor using real data in Portland, Oregon. Different performance measures were associated with various safety related goals.

- To maximize the safety of system operating conditions, performance measures were:
  - Number of incidents on system per yearly VMT
  - Customer perception of safety on transportation system
- To minimize transportation conflict points for all modes, developed measures were:
  - Number of incidents/injuries near conflict points per number of conflict points
  - Number of correctable crash sites funded for improvement
- To improve the clarity and design of operations delivery to system customers, measures were:
  - Annual survey questionnaire response
  - Percent of system route miles of with basic/advanced/predictive travel time information available.
  - Number of ATIS calls and website visits
- To improve incident detection verification and response, established performance measures were:
  - Average time between notification and response/arrival and clearance
  - Total duration of incidents

- ***Coordinated freeway and arterial operations handbook* (Urbanik et al., 2006).**

(Crash rate)

From a transportation facility user's point of view managing traffic in freeways and in adjacent arterial streets is the most important step to maximizing traffic efficiency. The handbook on Coordinated Freeway and Arterial (CFA) Operation is a guideline for transportation planner on managing traffic operations in freeway and arterial streets. Evaluating the benefits of CFA operations in safety issues are not easy, as there is no direct relationship. CFA operations have an obvious positive effect in traffic operation as they reduce the travel time significantly. On a large extent, the crashes happening due to stop-and-go traffic can be reduced by mitigating traffic congestion. In this study, to evaluate the effect of CFA on safety, the crash rate was used as performance measure.

6.3 Economics

6.3.1 Cost of Delay (Average value of time (dollar/person-hour)*total delay (person-hour))

6.3.2 Fuel Cost

- ***Generating Performance Measures from Portland's Archived Advanced Traffic Management System Data*** **(Bertini et al., 2002).**

(Cost of delay, and Fuel cost)

The primary objective of this study is to develop a set of measures affecting safety, mobility, economic and environmental using archived date in a corridor of Portland, Oregon. Two performance measures were established in this study to understand the economic impact: *Cost of Delay* and *Fuel Cost*. Cost of delay can be calculated by multiplying average value of time with the total delay in person hours. The total fuel cost of eastbound U26 was calculated to be $21.3 million per year.

6.4 Environment

6.4.1 Greenhouse Gas Emission

6.4.2 CO2 Emission

- **FDOT active arterial management (AAM) program (Melissa Ackert).**

(Greenhouse gas emissions)

This report discusses how Active Arterial Management (AAM) works, where it being applied, and FDOTs' regional climate action plan. It is observed that more than 45 percent of the region's greenhouse gas emission is a direct result of the transportation sector. One primary goal of regional climate action plan is to reduce greenhouse gas emissions by planning, designing, and prioritizing walkable, affordable communities supported by sustainable multimodal transportation options. Therefore, greenhouse gas is an important measure to evaluate the performance of AAM program. Reduction in emissions is calculated by multiplying delay savings (in veh-hrs) with emission (tons/hour) and dollar value. Agencies should make an effort to collect information that will allow for evaluation of the effectiveness of a strategy in reducing greenhouse gas emissions.

- ***Arterial Management: Traffic Control; its benefits, costs, and lessons learned: 2014 update report* (U.S. Department of Transportation, 2014).**

(CO_2 Emissions)

Arterial management systems manage traffic along arterial roadways by utilizing traffic detectors, traffic signals, and various means of communicating information to travelers. This report is based on past evaluation data contained in the ITS knowledge resources database, which is maintained to support informed decision making regarding ITS investments by tracking the effectiveness of deployed ITS. This report also summarizes the results of an eco-traffic signal timing model based on a case study. Preliminary modeling shows a reduction of CO_2 emissions for the entire corridor.

7 Freeway Management

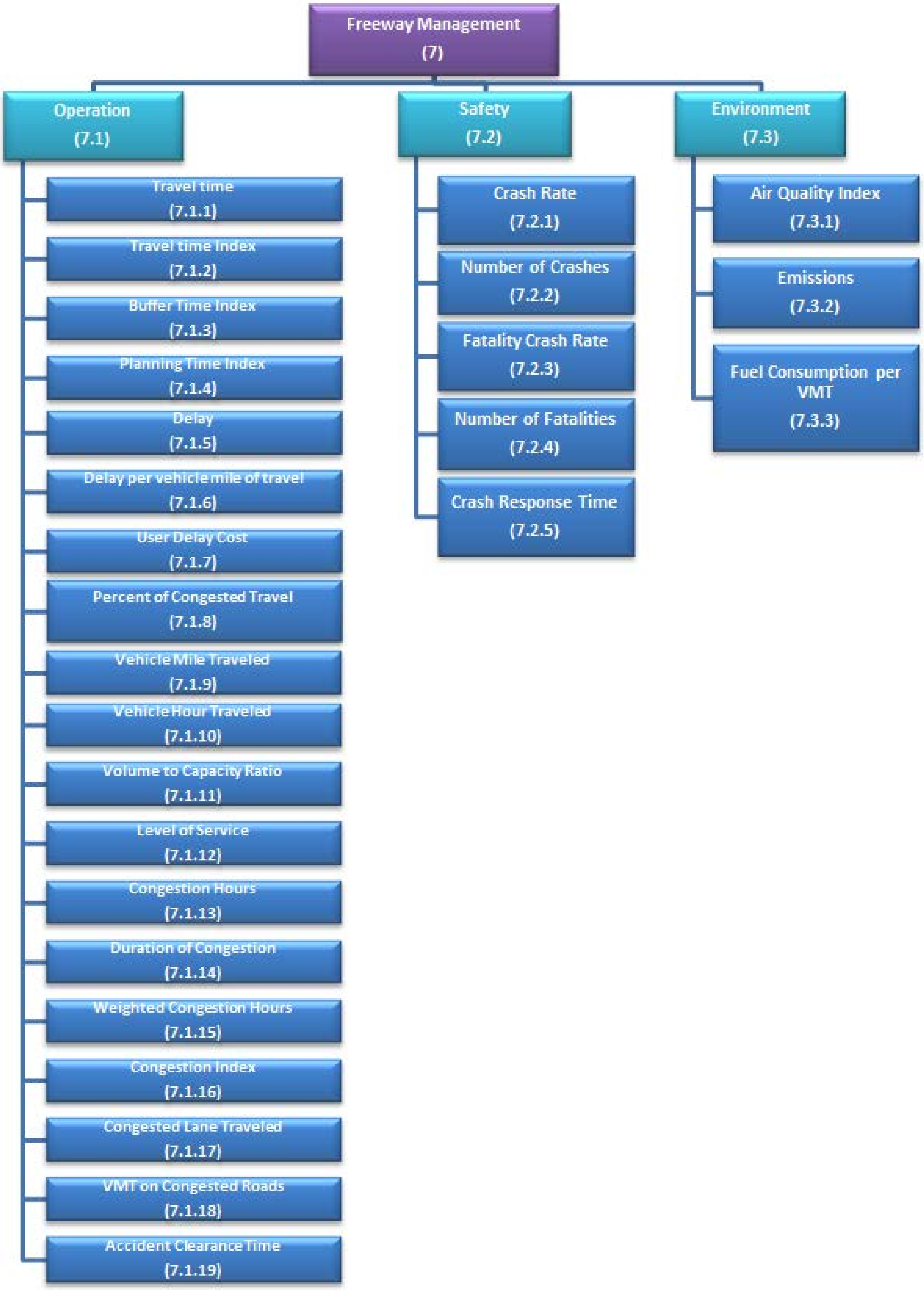

FIGURE 3.8: Freeway Management TSM&O strategy, categories and performance measures

7.1 Operations

7.1.1 Travel time

7.1.2 Travel time Index

7.1.3 Buffer Time Index

7.1.4 Planning Time Index

7.1.5 Delay

7.1.6 Delay per Vehicle Mile of Travel

7.1.7 User Delay Cost

7.1.8 Percent of Congested Travel

7.1.9 Vehicle Mile Traveled

7.1.10 Vehicle Hour Traveled

7.1.11 Volume to Capacity Ratio

7.1.12 Level of Service

7.1.13 Congestion Hours

7.1.14 Duration of Congestion

7.1.15 Weighted Congestion Hours

7.1.16 Congestion Index

7.1.17 Congested Lane Traveled

7.1.18 VMT on Congested Roads

7.1.19 Accident Clearance Time

- ***Operations-Oriented Performance Measures for Freeway Management Systems: Year 1* (Brydia et al., 2007).**

(VMT, Travel time, Delay per vehicle mile of travel)

This report illustrates first year accomplishments of using operation oriented performance measures in freeway systems. Freeway traffic management is associated with the control and guidance of traffic flow in access control highways to improve the overall mobility, safety, and environmental effect. Mobility of a freeway is concerned with the ease of traffic movement from one place to another. This report recommends several mobility oriented measures from a list of dozens performances measures to apply to particular situations. These are Vehicle miles of travel by congestion level, Travel time under congested conditions, Delay per vehicle mile of travel, Delay due to incidents, Lost time due to congestion, and Annual hours of delay.

- ***Integrated Corridor Management Analysis, Modeling and Simulation (AMS) Methodology* (Alexiadis, 2008).**

(Travel time, Delay, VMT, VHT)

This study sponsored by U.S. Department of Transportation defines an Analysis, and Modeling and Simulation (ASM) methodology to evaluate Integrated Corridor Management (ICM) strategies in corridor operations. In order to quantify how ICM strategies affect the mobility (how well the corridor moves people and freight) of the road, travel time and delay were two primary performance measures proposed in this study. Other proposed measures were Vehicle Miles Traveled (VMT), Person Miles Traveled (PMT), Vehicle Hours Traveled (VHT), Person Miles Traveled (PHT) and Person Hours Delay (PHD).

- ***Freeway management and operations handbook* (Neudorff et al., 2003).**

(Travel time, VMT, VHT, Delay, Level-of-Service, V/C)

Freeway Management and Operations Handbook is a book which provides various institutional and technical issues regarding operation, planning, design, and management of freeway network systems. This report identifies several measures to quantify the mobility, safety, and environmental performances of different strategies applied to freeway. Mobility performance measures identified by this report are:

- Origin-destination travel times
- Average speed or travel time
- Vehicle miles traveled (VMT) by congestion level
- Lost time or delay due to congestion
- Level of service or volume-to-capacity ratios
- Vehicle hours traveled or VMT per capita
- Person miles traveled (PMT) per VMT
- Customer perceptions on travel times
- Delay per ton-mile
- PMT per capita or worker
- Person hours traveled
- Passenger trips per household

- ***Guide to effective freeway performance measurement: Final report and guidebook* (Margiotta et al., 2006).**

(Travel time, Delay, VMT)

Freeways are defined as the highways with uninterrupted traffic flow. The guidebook on Effective Freeway Performance Measurements conducted by National Cooperative Highway Research Program (NCHRP) provides a comprehensive strategy to measure the performance of urban and rural highways. This guidebook recommends a set of performance measures to be used by different transportation agencies to evaluate the operational efficiency of a freeway: travel time, travel time index, total delay (vehicle), total delay (person), delay per vehicles, density, planning time index, buffer index, vehicle miles travelled, person miles travelled, throughput vehicle, and throughput person.

- ***Freeway management and operations handbook* (Neudorff et al., 2003).**

(Travel time index, Buffer index)

This freeway management and operations handbook summarizes several official and procedural topics related to planning, design, implementation, operation and management of freeway network. The primary problem reviewed by this report on freeway management is the congestion. It has been estimated by the Texas Transportation Institute (TTI) that the 75 largest metropolitan areas faced a total of 3.6 billion vehicle-hours of delay in 2000. One measure of congestion is travel time index, which signifies how much extra time it takes to make a trip during a peak period than other times of day. Travel time index on interstates increased by 12 percent from 1990 to 2000. Travel time index is typically calculated by dividing the peak period travel time by free-flow travel time. To evaluate the impact of freeway management on travel time reliability, buffer time index was introduced as a performance measure. Buffer time index indicates the amount of extra buffer time needed to be on time 95 percent of the time. Buffer time index is the most preferred measure for reliability because this percent value is distant and time neutral.

- **2011 Indiana Interstate Mobility Report—Summary Version (Remias et al., 2012).**

(Congested hours, Weighted congestion hours, Congestion index)

This report represents the performance measures which were developed by Indiana Department of Transportation to guide infrastructure investment decisions and assess outcomes. Congestion hours, Weighted congestion hours, and Congestion index are the performance measures to quantify interstates mobility in this report. An Indiana interstate route is considered congested when the average speed falls below 45 mph. Congestion hours are defined as the number of hours an interstate segment or series of segments has an average speed less than 45 mph. Number of congestion hours multiplied by the segment length in mile used to provide Weighted congestion hours. Finally, the Congestion index is defined as the number of weighted congestion hours divided by the aggregated total lane mileage. The report pointed out the application developed congestion performance measures.

- ***Using operation data for planning in the Delaware valley: first step*** **(Delaware Valley Regional Planning Commission, 2011).**

(Travel time index, Buffer index, Planning time index, Duration of congestion)

This report introduced the use of real time data in evaluation of the performance of the transportation system. Moreover, based on the quality of the collected and archived data, this report presented the use of operation data for planning purposes. Various transportation agencies throughout the Delaware Valley use traffic cameras, E-ZPass detectors, Global Positioning System (GPS) probes, and microwave sensors to collect information about traffic speed, travel time, and incidents. In this study, the ultimate goal of traffic operators and planners are specified toward the same things: congestion reduction, safety improvement, and efficiently moving people and goods. The performance measures used to evaluate transportation system are Travel time index, Speed, Buffer index, Planning time index, and Duration of congestion.

- ***Congestion & mobility report*** **(Michigan Department of Transportation, 2014).**

(Delay, User delay cost, Speed)

This report demonstrated the use of Probe data in providing some measures to monitor the performance of freeways in Michigan State. This document is for internal use to help MDOT regions, Transportation Service Centers (TSCs), and planners. The introduced measures in this report are helpful to identify congested areas, duration of congestion, corridor ranking, and cause of delay. Total delay, user delay cost, and average speed are the measures which were estimated from probe data to evaluate freeways operation. The User Delay Cost in this report was defined as multiplying delay, hourly volume, and hourly user cost.

- ***Performance Analysis of the Draft 2015 CLRP*** **(The National Capital Region, 2015)**

(VMT, Congested lane miles, VMT on congested roads)

The Constrained Long Rang Transportation Plan (CLRP) identifies regionally significant transportation projects and programs that are planned between now and 2040. In the 2015 amendment, which was presented to Transportation Planning Board, the Vehicle Miles Traveled, Congested Lane Miles, and VMT on Congested Roads were defined as congestion performance measures. These measures were categorized based on geographic differences to Regional Core, Inner Suburbs, and Outer Suburbs. The total number of congested lane miles is forecast to increase in all three sub-areas with the greatest expected increase in the inner suburbs. The share of lane miles that are congested is also expected to increase in all three sub-areas, but the highest increase is expected in the outer suburbs.

- **Performance measurement. An overview of NCDOT's strategy (North Carolina Department of Transportation)**

(Travel time index, Accident clearance time)

North Carolina executive performance measures are the basis for driving towards a better transportation network. These performance measures are outcome-based performance indicators and were established based on the best available data and information at that time. Various performance measures were suggested in this presentation regarding different transportation aspects. In order to improve the efficiency of transportation network in people movement, average statewide accident clearance time, and travel time index were defined as performance measures.

7.2 Safety

7.2.1 Crash Rate (Number of crashes per million VMT)

7.2.2 Number of Crashes

7.2.3 Fatality Crash Rate (Number of fatalities per VMT)

7.2.4 Number of Fatalities

7.2.5 Crash Response Time

- ***Operations-Oriented Performance Measures for Freeway Management Systems: Year 1*** **(Brydia et al., 2007).**

(Fatality crash rate, Number of fatalities, Crash response time)

A freeway is a type of road which has been designed for high speed vehicular movement without any interruption from sideways. Safety is the most important factor highway designers are focusing while designing a freeway. *Operations-Oriented Performance Measures for Freeway Management System: Year 1 Report* describes activities of a project using operation oriented performance measure in freeway management system. This report recommends a certain set of performance measures to evaluate the safety of freeway management system; they are Fatalities per vehicle mile traveled, Number of highway fatalities, Average duration of incidents, Average incident detection time, Average incident response time.

- ***Integrated Corridor Management Analysis, Modeling and Simulation (AMS) Methodology*** **(Alexiadis, 2008).**

(Number of crashes, Crash rates)

Integrated Corridor Management (ICM) is an initiative for the purpose of illustrating how Intelligent Transportation System (ITS) can efficiently and effectively deals with the movement of people and goods in major transportation corridors. *Integrated Corridor Management Analysis,* *Modeling and Simulation (AMS) Methodology* aims to discuss ICM strategies by an Analysis, Modeling, and Simulation (ASM) methodology. To evaluate the safety performance of ICM strategies on a corridor, two performance measures proposed by this study are number of crashes and crash rates.

- ***Freeway management and operations handbook*** **(Neudorff et al., 2003).**

(Crash rate, Crash response time)

Performance measures in transportation provide the basis for identifying the position and acuity of any problem (congestion, high crash rate) and evaluating the effectiveness of the implemented strategies. 'Freeway Management and Operations Handbook' identifies several performance measures to evaluate the safety goals of a freeway as follows:

- Number of crashes per VMT, year, trip, ton mile, and capita
- Number of high crash locations
- Response time to crashes
- Crash risk index
- Customer perception of safety
- Percentage of roadway pavement rated good or better
- Construction-related fatalities

- ***Guide to effective freeway performance measurement: Final report and guidebook*** **(Margiotta et al., 2006).**

(Number of crashes, Number of fatal crashes, Fatality crash rates)

This study conducted by National Cooperative Highway Research Program (NCHRP) provides transportation engineer support to maintain comprehensive freeway performance monitoring program. This report recommends a set of core and supplemental measures to evaluate the safety issues of any freeway. Total number of crashes, number of fatal crashes, overall crash rates, fatality crash rates and secondary crashes are the core recommended measures in this report.

- **Performance measurement. An overview of NCDOT's strategy (North Carolina Department of Transportation)**

(Crash rates)

North Carolina executive performance measures are the basis for driving towards a better transportation network and an improved level of service to the State of North Carolina. Various performance measures were suggested in this presentation regarding different transportation aspects. In order to improve the transportation network safety statewide network crash rate was defined as performance measures. The crash rate in this presentation was defined as total number of crash and fatality counts divided by 100 million vehicle miles traveled.

7.3 Environment

7.3.1 Air Quality Index (On a scale from 0 to 100 depending on the presence of O3, PM, CO, SO2)

7.3.2 Emissions (Emission rate of nitrous oxides, volatile organic compound (VOC), and carbon monoxide)

7.3.3 Fuel Consumption per VMT

- ***Operations-Oriented Performance Measures for Freeway Management Systems: Year 1* (Brydia et al., 2007).**

(Air quality index, Emission)

Air pollution is an important factor affecting the global ecosystem. While controlling naturally created air pollution is difficult, air pollution created by humans can be monitored and controlled. Transportation sector plays a vital role in air pollution as it generates high levels of carbon monoxide (CO), Hydrocarbons (HC) and Nitrogen Oxides (NO_x). This study concluded some specific performance measures applicable to transportation fields. They are:

- Air Quality Index (AQI)
- Number of days exceeding air quality standard Annually
- Percent of fuel consumption defined as cleaner Fuels
- On-road emission – ambient concentration (parts per million)
- On-road emission – emissions rate (parts per million per mile)
- Vehicle Occupancy Rate
- Pounds of transportation emissions per number of Vehicles
- Pounds of transportation emissions per vehicle miles traveled (VMT)

- ***Guide to effective freeway performance measurement: Final report and guidebook* (Margiotta et al., 2006).**

(Emission, Fuel consumption per VMT)

The application of performance measures in transportation has been growing for the last few years. In order to evaluate the environmental impacts of freeway management, the need of precise performance measures has been present for a long time. National Cooperative Highway Research Program (NCHRP) reported a set of performance measures which were established to quantify the environmental effects in freeways. The primary measures are associated with emission because vehicles emit high range of toxic compounds in the air. Recommended measures are:

- Nitrous Oxides (NOx) Emission Rate
- Volatile Organic Compound (VOC) Emission Rate
- Carbon Monoxide (CO) Emission Rate
- Fuel Consumption per VMT

8 High Occupancy Vehicle (HOV) Lanes

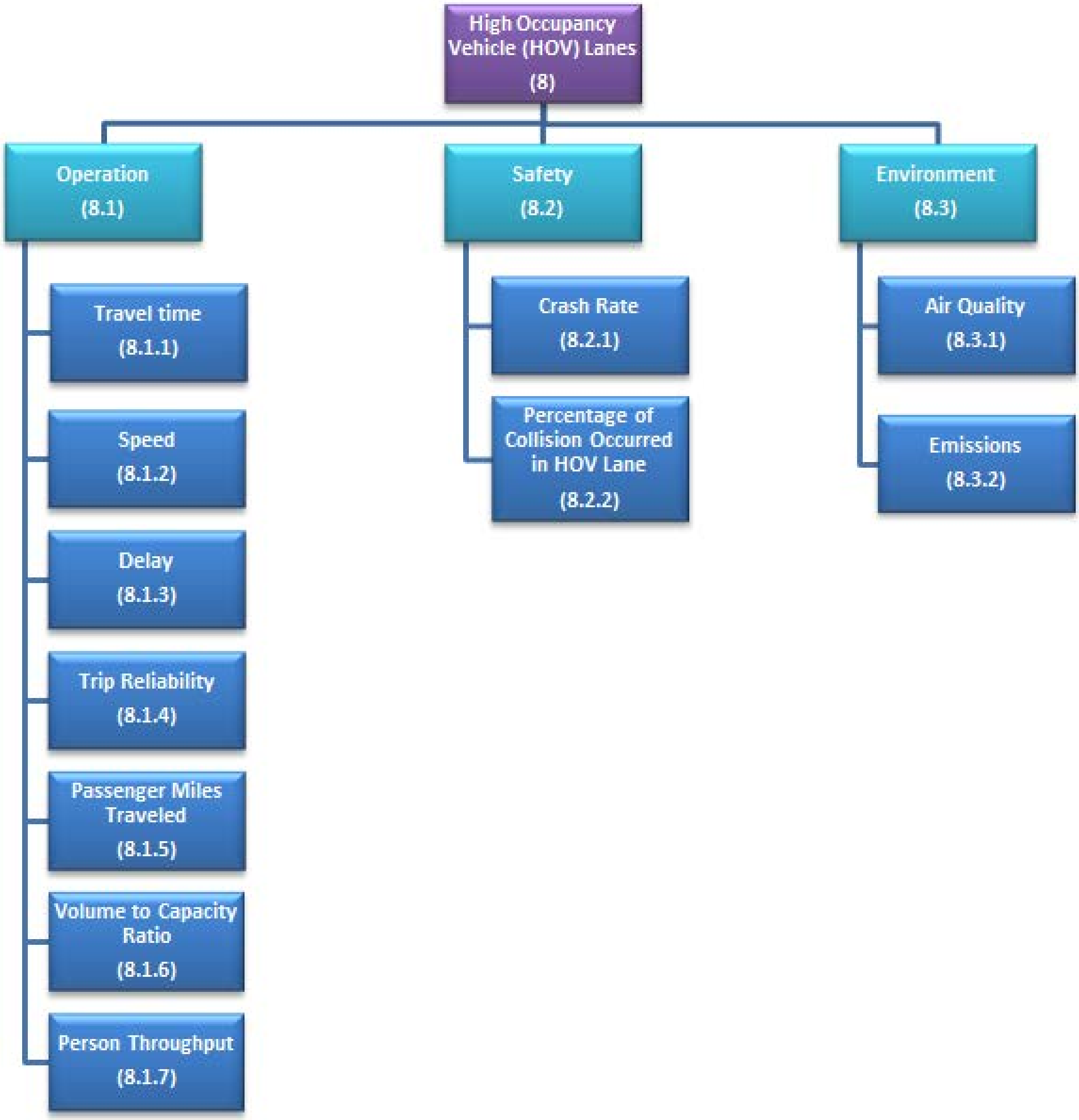

FIGURE 3.9: High Occupancy Vehicle (HOV) Lanes TSM&O strategy, categories and performance measures

8.1 Operations

8.1.1 Travel time

8.1.2 Speed

8.1.3 Delay

8.1.4 Trip Reliability (Percentage of time vehicle travels less than 45 mph)

8.1.5 Passenger Miles Traveled

8.1.6 Volume to Capacity Ratio

8.1.7 Person Throughput

- ***Operational Performance of High-Occupancy Vehicle (HOV) Facilities: Comparison of Contiguous and Limited Access HOV Lanes in California*** **(Jang et al., 2013).**

(Travel time, Passenger miles travelled (PMT))

This report focuses on the comparison between the general purpose (GP) lane, and two variations of HOV lanes (contiguous-access and limited access HOV lanes) using operational measures like travel speed, travel time and congestion.

The main objective of an HOV lane is to provide mobility and encourage passengers to use carpools and public transport. Therefore, travel speed and passenger miles travelled are direct measure to evaluate the performance of HOV facility. After examining extensive data, this report concluded that travel speed is less in HOV lanes than GP lanes, and HOV lanes carry more people-mile than GP lanes. Between contiguous access and limited access HOV lanes, contiguous HOV lanes shows greater difference compared with GP lanes. The volume of passengers per mile in both types of HOV lanes demonstrates similar outcomes in comparison with GP lanes

- ***A review of HOV lane performance and policy options in the United States*** **(Chang et al., 2008).**

(Travel speed, Volume over Capacity, Travel delay)

This study conducted a review to evaluate the performance of existing HOV lanes in the United States. HOV lanes are exclusive lanes for peak hour or longer for vehicle with two or more passengers to encourage the vehicles to travel with more passengers through these few lanes. In this report, operational performance of HOV lanes is assessed by Volume of Capacity (V/C), Travel Speed (mph), Level of Service (LOS), Corridor Travel Time, and Vehicle Travel Delay. All this performance measures were determined both in peak hours and on a daily basis.

- ***HOV lane performance monitoring: 2000 report executive summary*** **(Nee et al., 2001).**

(Travel speed, Trip reliability)

High occupancy vehicle (HOV) lanes are an exclusive traffic lane reserved for the vehicle with two or more passengers, including carpools, vanpools and transit buses. This report, on *HOV Lane Performance Monitoring*, portrays the findings of a monitoring project of HOV lane use in Puget Sound area. Extensive monitoring, data collection, and analysis were concluded to evaluate the several operational measures in HOV lanes in comparison with general purpose (GP) lanes. In this report, performance measures are travel time, travel speed, trip reliability, and congestion. The results demonstrated that the time needed to traverse a particular route in HOV lanes is much less than in GP lanes. Travel speed and trip reliability measures are illustrated together in this report with reference to state policy standard which requires an average speed of 45 mph or better, 90 percent time in the peak hour. Congestion is another measure to evaluate the performance of HOV lanes. This study shows on average, in HOV lanes vehicle encounter heavy congestion in morning and evening peak hour while traffic is free for the rest of the day.

- ***Maryland state highway mobility report – 2nd edition*** **(O'Malley and Brown, 2013)**

(Person throughput)

This Report on Maryland State Highway Mobility summarizes the mobility related efforts, and highlights successes, challenges and strategies being utilized for transportation services improvement. High occupancy vehicle (HOV) lanes promote carpooling, van, and bus usage to maximize the person throughput instead of just vehicle throughput. HOV lanes offer a viable alternative transportation mode for commuters and increase person throughput. It is observed in this report that the person throughput for I-270 and US 50 is higher in the HOV lanes than the non-HOV or general purpose lanes, even though the HOV lane vehicle numbers are lower. Accordingly, it was concluded that person throughput, instead of vehicle throughput is a viable measure to evaluate the performances of HOV lanes.

8.2 Safety

8.2.1 Crash Rate (Crashes per 100 million VMT)

8.2.2 Percentage of Collision Occurred in HOV Lane

- ***Crash analysis of selected high-occupancy vehicle facilities in Texas: methodology, findings, and recommendations*** **(Ranft et al., 2013).**

(Crash rate)

High Occupancy Vehicle (HOV) lanes provide users with a facility to travel faster with 2 or more passengers through a restricted lane. The primary objective of this report is to study different HOV lanes in Texas and summarize the safety issues related with HOV lanes. Crash rate was designated as the foremost measure to evaluate the safety of HOV lanes. The results of this research reflect that there is no significant change in crash rates for barrier separated HOV lanes, while buffer-separated HOV lanes results higher corridor injury crash rates than no-HOV lane scenario. Access points in HOV lanes were found to be the critical spots where most of the crashes happened.

- ***Safety performance of high-occupancy-vehicle facilities: Evaluation of HOV lane configurations in California* (Jang et al., 2009).**

(Percentage of collision that occurred in HOV lane)

This study was conducted to evaluate the safety performance of two distinct configurations of HOV lanes, continuous and limited. The percentage of collision was selected as a measure to compare the performance of continuous and limited HOV lane. The outcomes of this report suggest that in comparison with continuous HOV lanes, the percentage of collision is higher on limited access HOV lanes. This report also evaluates the relationship between collision rate on HOV lane and geometric features of road, like shoulder width, length of access etc.

8.3 Environment

8.3.1 Air Quality (Vehicle travel delay*Gallon of fuel/hour*Passenger car average emission of CO+NOx+VOC)

8.3.2 Emissions (Emission of CO,NOx, and VOC)

- ***A review of HOV lane performance and policy options in the United States* (Chang et al., 2008).**

(Air quality, Emission)

HOV lanes were originally proven as a means to increase person throughput in the transportation system, among other potential benefits like providing reliable transit trip times and increasing roadway capacity while benefiting air quality. This report on HOV lane performance provides an assessment of existing HOV lane facilities in United States. The purpose was to evaluate and quantify the effect of HOV policy changes on operational performance and environmental measures. Two main environmental measures were examined: air quality performance and carbon Dioxide. These measures are directly related to quantity of gasoline conserved.

- ***HOV lane performance monitoring: 2000 report executive summary* (Nee et al., 2001).**

(Emission)

The report, *Determining the Effectiveness of HOV lanes* by Institute of Transportation Studies, University of California, Berkeley, developed an inclusive list of references from a comprehensive literature review and summarized the present knowledge regarding the impact of HOV lanes on air quality. To determine the environmental impact of HOV lane, emission rate was evaluated. It has been concluded from this study that adding a HOV lane in a no HOV lane highway certainly increases the emission and affects the air quality negatively.

9 Pricing/Toll Roads

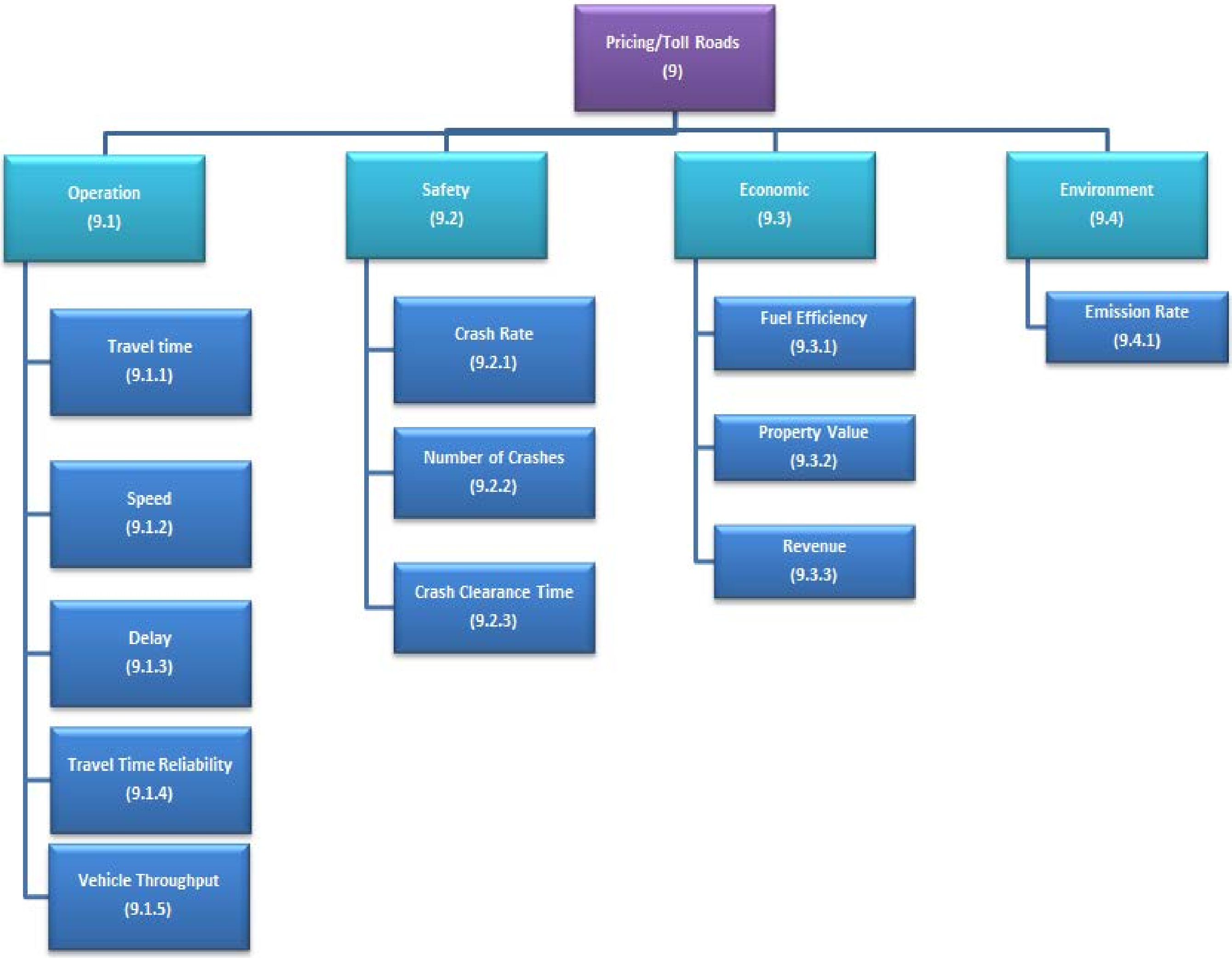

FIGURE 3.10: Pricing/Toll Roads TSM&O strategy, categories and performance measures

9.1 Operations

9.1.1 Travel time

9.1.2 Speed

9.1.3 Delay

9.1.4 Travel Time Reliability (Variation in travel time)

9.1.5 Vehicle Throughput

- ***Economic Benefits of Toll Roads Operated by the Transportation Corridor Agencies: Executive Summary* (Munroe et al., 2006).**

(Travel time)

Traffic congestion is one of the major problems of road networks. Governments are implementing various strategies over the year to minimize congestion. One such strategy is the use of toll roads, which offer passengers a congestion free travel in exchange of a price. It is clearly suggested in this report that toll roads significantly reduce traffic congestion. Moreover, it has been noticed that toll roads handle a greater number of vehicles than non-toll roads without congestion problems.

- ***Operational Performance Management of Priced Facilities* (Burris et al., 2011).**

(Travel time, Speed, Delay)

Priced facilities in transportation management system provide passengers with a speedy travel experience in exchange for a particular price. This paper evaluates operational performance management of priced facilities. To evaluate the operational impact of priced facilities, this study provides with a set of performance measures and their implementation guidelines. The candidate measures of this research are Travel Time, Travel Speed and Travel Delay.

- ***A benefit-cost analysis of road pricing in Downtown Seattle* (Danna et al., 2012).**

(Travel time reliability)

In order to determine if road pricing options would be beneficial in downtown Seattle, this paper conducted the cost benefit analysis and evaluated the key benefits and costs associated with potential cordon-based road pricing. The measures quantified were travel time, travel time reliability, emission, and accidents. It was summarized that road pricing reduces traffic volume which results lower variation in travel time. Studies from London and Stockholm suggest the reliability benefits be approximately one-third of the benefits of travel time savings. Assuming this relationship between travel time benefits and reliability holds for Seattle, the value of travel time reliability will be $26 million.

- ***Congestion pricing: A primer* (Federal Highway Administration, 2006).**

(Vehicle throughput)

Congestion pricing is a way to shift purely discretionary rush hour highway travel to other transportation modes or to off-peak periods, taking advantage of the fact that the majority of rush hour drivers on a typical urban highway are not commuters. To quantify the effectiveness of congestion pricing, vehicle throughput is an important performance measure. Vehicle throughput on a freeway is the number of vehicles that get through over a short period such as an hour. Once freeway traffic exceeds a certain threshold level, both vehicle speed and vehicle throughput drop precipitously. With peak-period highway pricing, a variable toll dissuades some motorists from entering freeways at those access points where traffic demand is high. It is observed that each variably priced lane in the median of State Route 91 in Orange County, California, carries twice as many vehicles per lane as the free lanes during the hour with heaviest traffic. Pricing has allowed twice as many vehicles to be served per lane at three to four times the speed on the free lanes.

- **Chicago Metropolitan Agency for Planning (CMAP). http://www.cmap.illinois.gov-/mobility/explore#/**

(**Speed**)

The Chicago Metropolitan Agency for Planning (CMAP) was created in 2005 as the official regional planning organization for the northeastern Illinois counties. Referred to the GO TO 2040 plan, transportation system is important factor to sustain the region's economy and quality of life. Congestion is one of the issues in metropolitan Chicago which costs billions of dollars annually in wasted time and fuel, decreased productivity, inefficient freight movements, and pollution. Congestion pricing is one of the activities that CMAP believes can reduce the congestion. To measure the effectiveness of congestion reduction activities, CMAP tracks how often speed on limited access highways fall below 45 mph.

9.2 Safety

9.2.1 **Crash Rate** (Crashes per 100 million VMT)

9.2.2 Number of Crashes

9.2.3 Incident Clearance Time

- ***Operational Performance Management of Priced Facilities* (Burris et al., 2011).**

(Crash rate, Number of crashes, Crash clearance time)

The report on *Operational Performance Management of Priced Facilities* (High Occupancy Vehicle lanes, Toll roads etc.) reviewed literature and established a set of guidelines to identify and select performance measures of pricing facilities. In order to evaluate the safety impacts of toll roads, the measures this report identified are Crash Rate, Number of Crashes, Incident Rate, and Incident Clearance Time. It also developed a guideline on how to evaluate each of the measures.

- ***Effects of Open Road Tolling on Safety Performance of Freeway Mainline Toll Plazas* (Yang et al., 2012).**

(Crash rate)

Toll plazas are the primary means of collecting tolls of any highway or roads. Open road tolling system was developed to ensure operations of toll plaza even when vehicles are travelling in high speed. The primary objective of this report is to evaluate the effects of open road tolling on safety performance of mainline toll plazas. This open road tolling on freeway transforms barrier tollbooth to express lane making it capable to collect tolls automatically with high speed. Crash rate was used as the candidate performance measure in this study to evaluate the safety impact of open road toll plazas. The results show that crash rates increases with the number of barrier tollbooths, and the explanation was that the drivers are expected to be confused while choosing appropriate toll lane. Analysis of this report supports that implementation of open road tolling system with express electronic toll collection lane reduces crash frequency at toll plazas and positively affect the safety.

- ***A benefit-cost analysis of road pricing in Downtown Seattle*** **(Danna et al., 2012).**

(Crash rate)

Use of traffic tolls is increasing everyday around the world. Not much research has been done with safety effects of this policy. This paper focuses on the safety issues of implementing toll plaza in road. It has been suggested that crash rates increase due to the setting a tollbooth in a particular road. The explanation behind this measure is that the vehicles that do not want to pay for higher infrastructure road travel to a lower quality contiguous road and these roads are not constructed to handle such high level of traffic in safety standards.

9.3 Economics

9.3.1 Fuel Efficiency (Vehicle travel distance per gallon of fuel consumed)

9.3.2 Property Value

9.3.3 Revenue

- ***Economic Benefits of Toll Roads Operated by the Transportation Corridor Agencies: Executive Summary*** **(Munroe et al., 2006).**

(Fuel efficiency, Property value)

A toll road is a road pricing facility implemented to help recoup the cost of road construction and maintenance. Subsequently, new road construction offers the passengers a congestion free and high speed travel movement. This report on Economic Benefits of Toll Roads Operated by the Transportation Corridor Agencies demonstrates the economic impact of toll roads in California. By reducing traffic congestion, toll roads are improving fuel efficiencies of vehicle. This report illustrates a total fuel saving of 2 million gallons per year which translates a benefit of $7 billion dollar per year. Another significant measure is property value, which evaluates the economic impact of toll road. It has been observed that property values of the places that have access to toll roads are higher than other neighborhoods.

- ***Using road pricing revenue: economic efficiency and equity considerations*** **(Litman, 1996).**

(Revenue)

This paper examines how economic efficiency, equity, external costs, and political feasibility can help determine the distribution of road pricing revenue. Economic efficiency is concerned with the use of society's resources to achieve maximum net benefit. Road pricing increases efficiency by rationing road capacity with less waste than queuing. This benefit is unaffected by the allocation of road pricing revenue. From an overall economic efficiency perspective, the revenue must be used to benefit society; the more beneficial the more economically efficient the program. There is no requirement, however, that the money be allocated in any particular way.

9.4 Environment

9.4.1 Emission Rate (Emission rate of NOx, CO, PM)

- ***Use of Performance Measurement to Include Air Quality and Energy Into Mileage-based User Fees* (Farzaneh et al., 2012).**

(Emission rate)

Road pricing is the practice of charging motorist for using certain roads for particular amount of time or all the time to reduce traffic congestion. This report developed the use of performance measures to comprise air quality into a certain type of road pricing; mileage based user fees. The primary measure this report used to include air quality into mileage based user fees is emission rate. Vehicle miles traveled (VMT), vehicle emission rating, vehicle fuel economy, vehicle age, time traveled at a speed greater than optimum air quality speed, and time spent aggressively accelerating are factors that affect emission rate directly or indirectly. These factors were quantified to associate air quality into mileage based user fees.

10 Ramp Metering

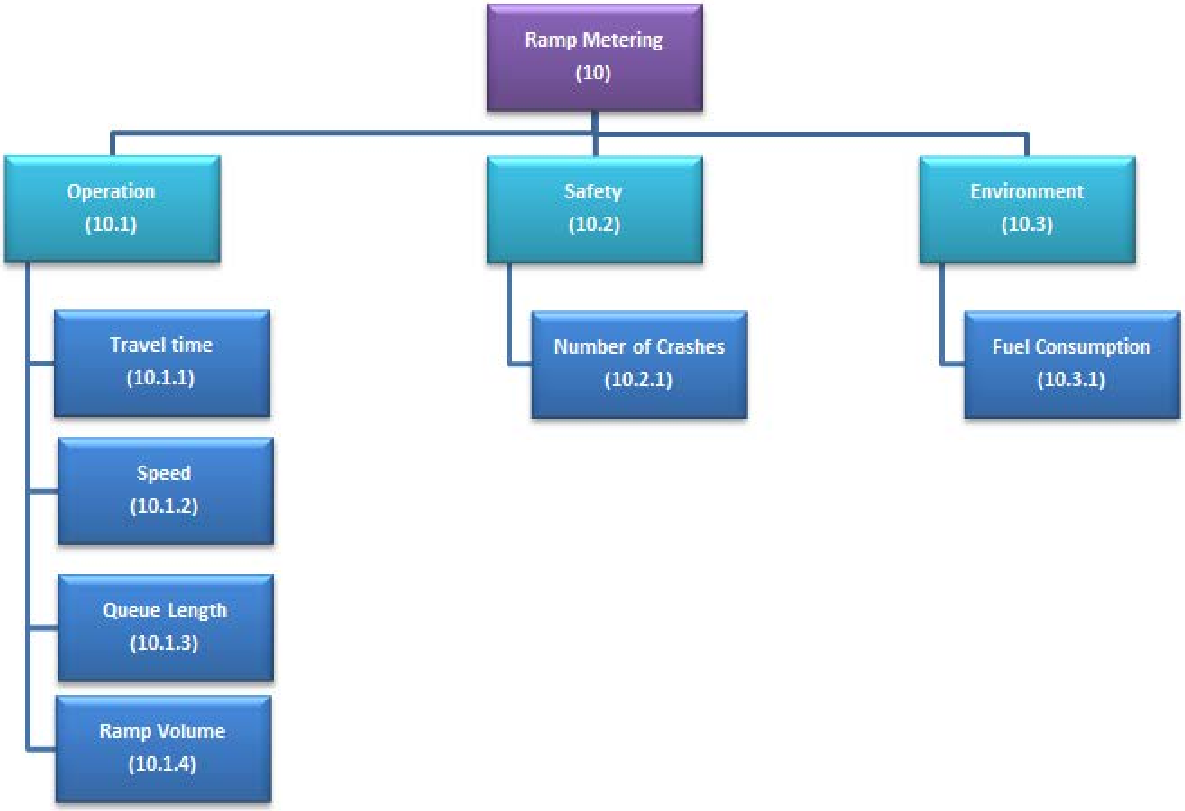

FIGURE 3.11: Pricing/Toll Roads TSM&O strategy, categories and performance measures

10.1 Operation

10.1.1 Travel time

10.1.2 Speed

10.1.3 Queue Length

10.1.4 Ramp Volume

- ***Managed Lanes and Ramp Metering Manual Part 4: Ramp Metering Performance Measurement Plan*** **(Nevada Department of Transportation, 2013).**

(Travel time)

The report, *Ramp Metering Performance Measurement Plan* uses mobility to address the performance of ramp metering on road network. Travel time measure is estimated to evaluate travel mobility impact. An effective way to estimate travel time measure is on a per trip basis, since it reflects the user's travel experience. The evaluation results on US 95 between Rancho river and Craig Road demonstrate that ramp meter significantly reduces the congestion.

- ***Twin Cities Ramp Meter Evaluation.*** **Pursuant to Laws 2000: Chapter 479 (Minnesota Department of Transportation, 2001)**

(Travel time, Speed)

The objective of the study; *Twin Cities Ramp Meter Evaluation* is to perceive and summarize the performance measures in order to evaluate the effect of eliminating ramp meters for a certain amount of time on safety, mobility, and environment. The results of this study illustrate that without eliminating ramp metering, speed decreases by 18 mile per hour in peak hour, which represents an increase of 22 percent in freeway travel time. Moreover, significant traffic congestion was made at the outside corridors due to the absence of metering strategy. Using travel time measure, this report summarized the worse traffic conditions without ramp meter.

- ***Evaluating Effectiveness of Ramp Meters*** **(Levinson and Zhang, 2004).**

(Travel time)

This report demonstrates the effectiveness of turning on the ramp meters for two weeks in the Twin Cities. Using travel time and speed as performance measures, it was found that ramp metering is an effective strategy to reduce the congestion. The results of this research demonstrate that travel delay per km decreases from 82 sec to 68 sec, and travel speed of the network increases from 37 to 62 Km/h with a ramp meter. System productivity was also measured to assess the mobility which showed 64% increase in system productivity.

- ***Methodologies for Estimating Metered On-ramp Vehicle Queue Length*** **(Jingcheng et al., 2007)**

(Queue length)

The study "Methodologies for Estimating Metered On-ramp Vehicle Queue Length" discusses three types of methods for estimating on-ramp queue length, and compares them with real world operation use. On-ramp queue length is an important measure to evaluate the ramp meter performance. Therefore, the ability to monitor metered on-ramp vehicle queue length accurately in real time and adjust metering rate correspondingly will improve ramp meter performance at the system level and help to create new ramp metering algorithms. One model of diamond interchange was developed, and it was found that on-ramp queue spillback would directly reduce capacity and increase delay for the diamond interchange traffic.

- ***WisDOT Ramp metering and control plan*** **(Wilbur Smith Associates, 2006).**

(Ramp volume)

Ramp meters are traffic signals on freeway entrance ramps that break up clusters of vehicles entering the freeway to make merging safer. The objective of this report is to lead the development of an institutional and procedural plan for integrating the implementation criteria for ramp control strategies into statewide planning and programming processes. Ramp volume is a preliminary criterion of ramp metering implementation when considering deployment of a ramp meter system. At least 240 vehicles per hour per lane for any hour is suggested by this study to implement ramp metering. Ramp metering operations assume that the traffic conditions are appropriate for this tool to be effective. Similar to the maximum metering rate, if the total ramp volumes are too high, then metering is not the correct tool. The number is initially set at 1,200 vehicles per hour.

10.2 Safety

10.2.1 Number of Crashes

- ***Managed Lanes and Ramp Metering Manual Part 4: Ramp Metering Performance Measurement Plan* (Nevada Department of Transportation, 2013).**

(Number of crashes)

Ramp Metering Performance Measurement Plan recommends several measures to evaluate the performance of ramp metering strategy and guides how to report those performance measures efficiently throughout State of Nevada. Number of crashes is the most effective measure to assess traffic safety. It is mentioned that sufficient sample size throughout longer term should be used to validate crash rate, and proper caution must be taken to develop and analyze crash data.

- ***Twin Cities Ramp Meter Evaluation.* Pursuant to Laws 2000: Chapter 479 (Minnesota Department of Transportation, 2001).**

(Number of crashes)

A significant measure *Twin Cities Ramp Meter Evaluation* estimates is the *number of crashes* to evaluate the safety performance of the network without ramp meter. During same amount of time in the same freeway, 261 crashes were reported with the use of the ramp meter, which increases to 476 crashes without the ramp meter. An average of additional 4 crashes per day resulted without the ramp meter, and the types of crash indicate that the crashes were mainly in the merging area due to lack of a meter.

10.3 Environment

10.3.1 Fuel Consumption

- ***Managed Lanes and Ramp Metering Manual Part 4: Ramp Metering Performance Measurement Plan* (Nevada Department of Transportation, 2013).**

(Fuel consumption)

Environmental effects of ramp metering are generally measured as difference in fuel assumption. This report on *Ramp Metering Performance Measurement Plan* demonstrates some challenges to evaluating this performance. For example, implementing a ramp meter will reduce the fuel consumption in freeway, but increase it at the queue segment. So, these situations should be taken to account when applying this measures.

- ***Twin Cities Ramp Meter Evaluation.*** **Pursuant to Laws 2000: Chapter 479 (Minnesota Department of Transportation, 2001).**

(Fuel consumption)

The only one performance measure of the study *Twin Cities Ramp Meter Evaluation* which was unfavorable to ramp meter is fuel consumption. As a ramp meter ensures higher speed in the freeway, it increases the fuel consumption per vehicle. This report concludes that ramp meter results an annual increase of 5.5 million gallons of fuel consumption which causes an annual loss of $8 million.

11 Geometric Design

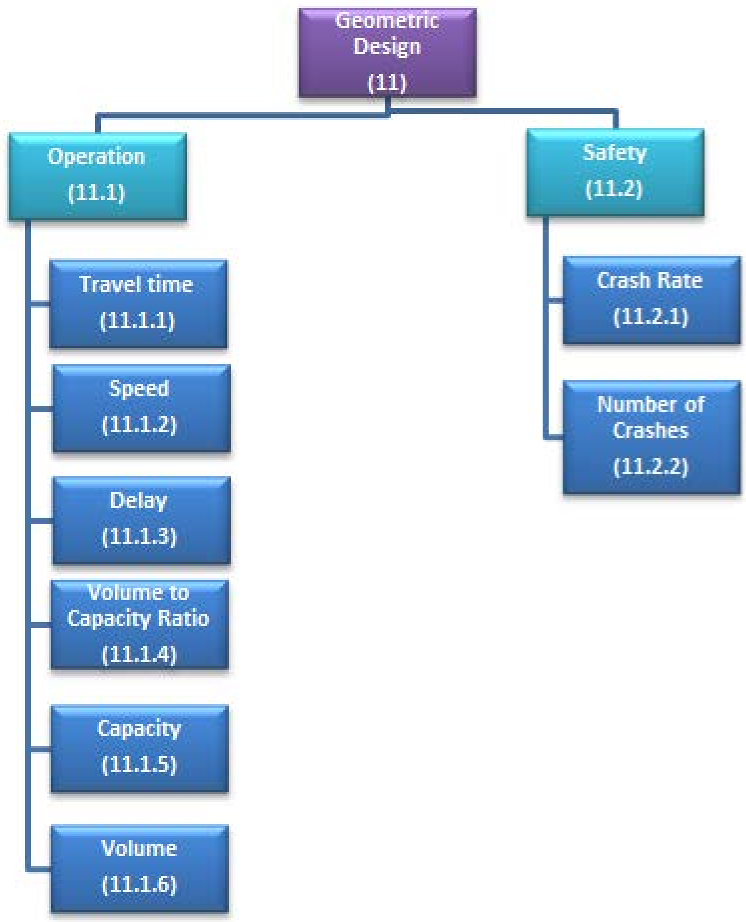

FIGURE 3.12: Geometric Design TSM&O strategy, categories and performance measures

11.1 Operations

11.1.1 Travel time

11.1.2 Speed

11.1.3 Delay

11.1.4 Volume to Capacity Ratio

11.1.5 Capacity

11.1.6 Volume

- ***Performance-based Analysis of Geometric Design of Highways and Streets* (Ray et al., 2014).**

(Travel time, Speed, Delay, Volume to capacity ratio)

Geometric design of highways deals with the dimension and layout of the visible elements of the highway, which fulfills the requirements of driver and the vehicle like comfortability, efficiency and safety. National Cooperative Highway Research Program (NCHRP) conducted a study called *Performance-Based Analysis of Geometric Design of Highway and Streets*, which developed an approach to evaluate the performance measures of decision making regarding geometric design of road. Geometric design of road influences mobility of vehicles. Mobility can be defined as the effective movement of various vehicles from one place to another using streets and highways. This report categorizes different performance measure while evaluating the operational impact of road such as travel time, freeway speed, delay, volume-capacity ratio, and etc.

- ***Geometric design consistency on high-speed rural two-lane roadways* (Wooldridge, 2003).**

(Travel speed)

National Cooperative Highway Report Program (NCHRP) provides some rules in the study on *Geometric Design Consistency on High-Speed Rural Two-Lane Roadways* useful for experts to review and design highways. Geometric design of roadway is concerned with the visible features of the roadway, which increases operational efficiency and safety. Travel speed is an appropriate performance measure to evaluate the operational impact of geometric design of road. For example, if there is a driveway situated along a two lane highway, it will reduce the travel speed due to the conflict point between the through traffic and turning traffic.

- ***Recent geometric design research for improved safety and operations*** **(Fitzpatrick and Wooldridge, 2001).**

(Capacity)

The report *Recent Geometric Design Research for Improved Safety and Operations* summarizes the findings of research published in 90s regarding improvement of safety and operation associated with geometric design of road. Geometric designs such as lane width, shoulder lane, intersection, and interchanges have a major influence on traffic operation. Optimum design of the physical elements of a road ensures efficient operation of traffic. One of the many key findings of this study is that in a congested urban corridor, capacity can be increased by using shoulders as travel lane and/or narrowing travel lane on a freeway. Also, reducing the number of lanes in an urban road can improve the operation of that corridor.

11.2 Safety

11.2.1 Crash Rate (Crashes per million VMT)

11.2.2 Number of Crashes

- ***Performance-based Analysis of Geometric Design of Highways and Streets*** **(Ray et al., 2014).**

(Number of crashes)

Geometric design is the section of Transportation Engineering concerning the positioning of physical elements of roads and highways according to the standards and constrains. The report *Performance-Based Analysis of Geometric Design of Highways and Streets* institutes a methodology which specialists can use to evaluate the performance measures of decision making regarding geometric design of highways. The form of highways, streets, interchanges, and intersections has a direct impact on safety measures of the users. Number of crashes is the key performance measure to quantify the safety impact of road geometry. For example, single-lane roundabouts result in fewer crashes than two-way, stopped control intersections. Thus, it can be concluded that proper geometric design of a highway will reduce crashes and their severity.

- ***Geometric design consistency on high-speed rural two-lane roadways*** **(Wooldridge, 2003).**

(Crash rate)

The report *Geometric Design Consistency on High-Speed Rural Two-Lane Roadways* was conducted by National Cooperative Highway Report Program (NCHRP). This study offers guidelines on geometric design consistency useful for practitioner to directly design or review existing highways. Inconsistent geometric features like horizontal and vertical alignment changes, lane drops, and lane width reduction can increase crash rates by compromising the safety of roadways. Historically, the most prominent geometric feature that influences safety is the horizontal curve. It has been suggested in this report that horizontal curves with design speed less than the desired speed of drivers' increases crash potential.

- ***Recent geometric design research for improved safety and operations* (Fitzpatrick and Wooldridge, 2001).**

(Crash rate)

This synthesis report on *Recent Geometric Design Research for Improved Safety and Operations* analyzed and summarized the literature review of research which focused on improvement of safety and operation through geometric design of roadways. Geometric design of roadways consists of the physical elements which provide efficiency and safety with an optimum cost. Several studies suggest that there is a direct relationship between geometric elements and safety. Curves with sharper bends result higher rate of crashes. Interchanges, intersections, and cross-sections of the road also affect the crash rate. One of the many recommendations this study offers is to introduce some alternative intersection design like roundabouts in order to improve the safety.

12 Traffic Signal Program Management

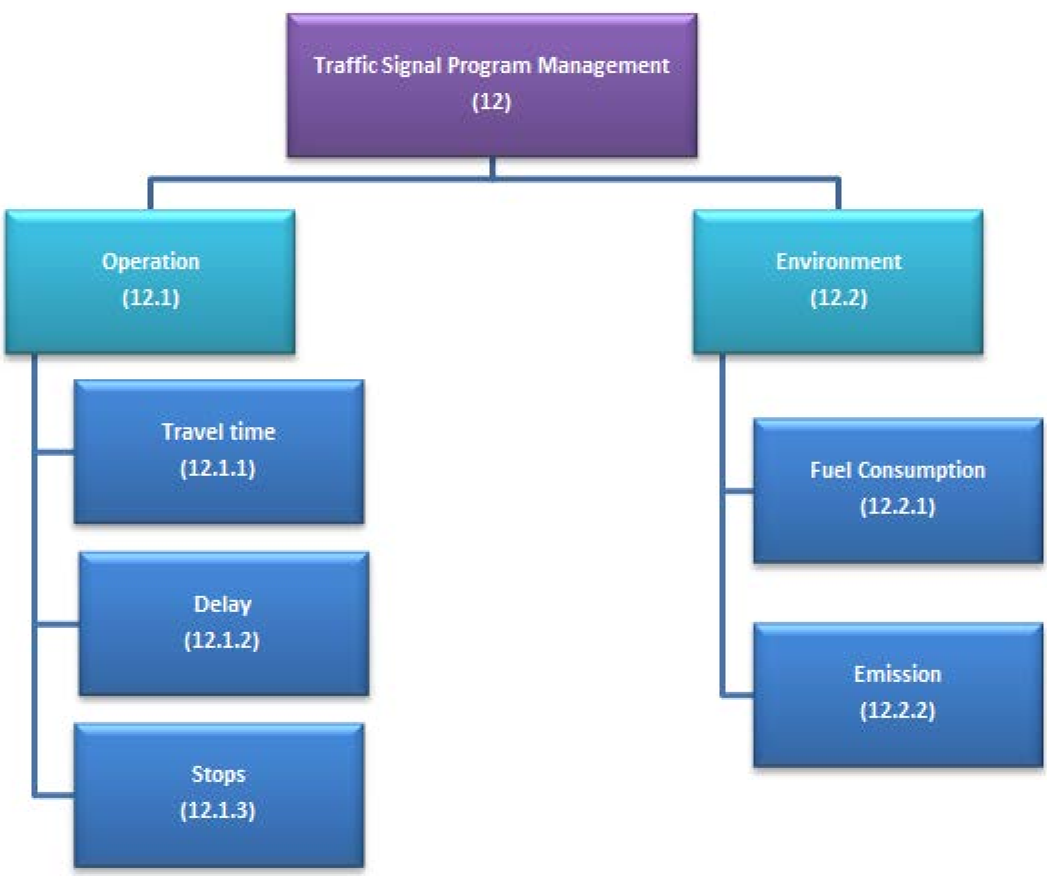

FIGURE 3.13: Traffic Signal Program Management TSM&O strategy, categories and performance measures

12.1 Operations

12.1.1 Travel time

12.1.2 Delay

12.1.3 Stops

- ***Best Practices In Regional, Multiagency Traffic Signal Operations Management,*** **Project 20-68A, Scan 07-04 (National Cooperative Highway research Program, 2013).**

(Travel time, Delay, Stops)

The findings of this study result from a scan workshop of domestic regional traffic signal operations program in the United States. Different types of organizational structures, institutional agreements and arrangements, and operational policies were examined in order to manage and operate traffic signal systems from a regional perspective throughout the United States. It was found that various regions have different regional traffic signal operation program objectives, which reflect the needs and priorities of the local operating agencies. To illustrate the benefits of traffic signal operation management program, most of the regions generated pilot or demonstration projects include a before-and-after comparison of travel time, delay, and number of stops.

12.2 Environment

12.2.1 Fuel Consumption

12.2.2 Emission (Emission of NOx and CO2)

- ***Best Practices In Regional, Multiagency Traffic Signal Operations Management,*** **Project 20-68A, Scan 07-04 (National Cooperative Highway Research Program, 2013).**

(Fuel consumption, Emission)

Seventeen regional traffic signal operation programs participated in the scan 07-04. This program created a sample of state and local regional traffic signal operations in terms of program size, responsible agency, and maturity. This report provided a good cross-section of the types of regional traffic signal operation programs that exist in the United States. Goals and objectives of this program vary for different agencies and are critical to define high priority needs of the region at the beginning. In order to illustrate the benefits of traffic signal operation management program on economic level, most of the regions generated pilot or demonstration projects include a before-and-after comparison of fuel consumption and emissions.

13 Signal Timing

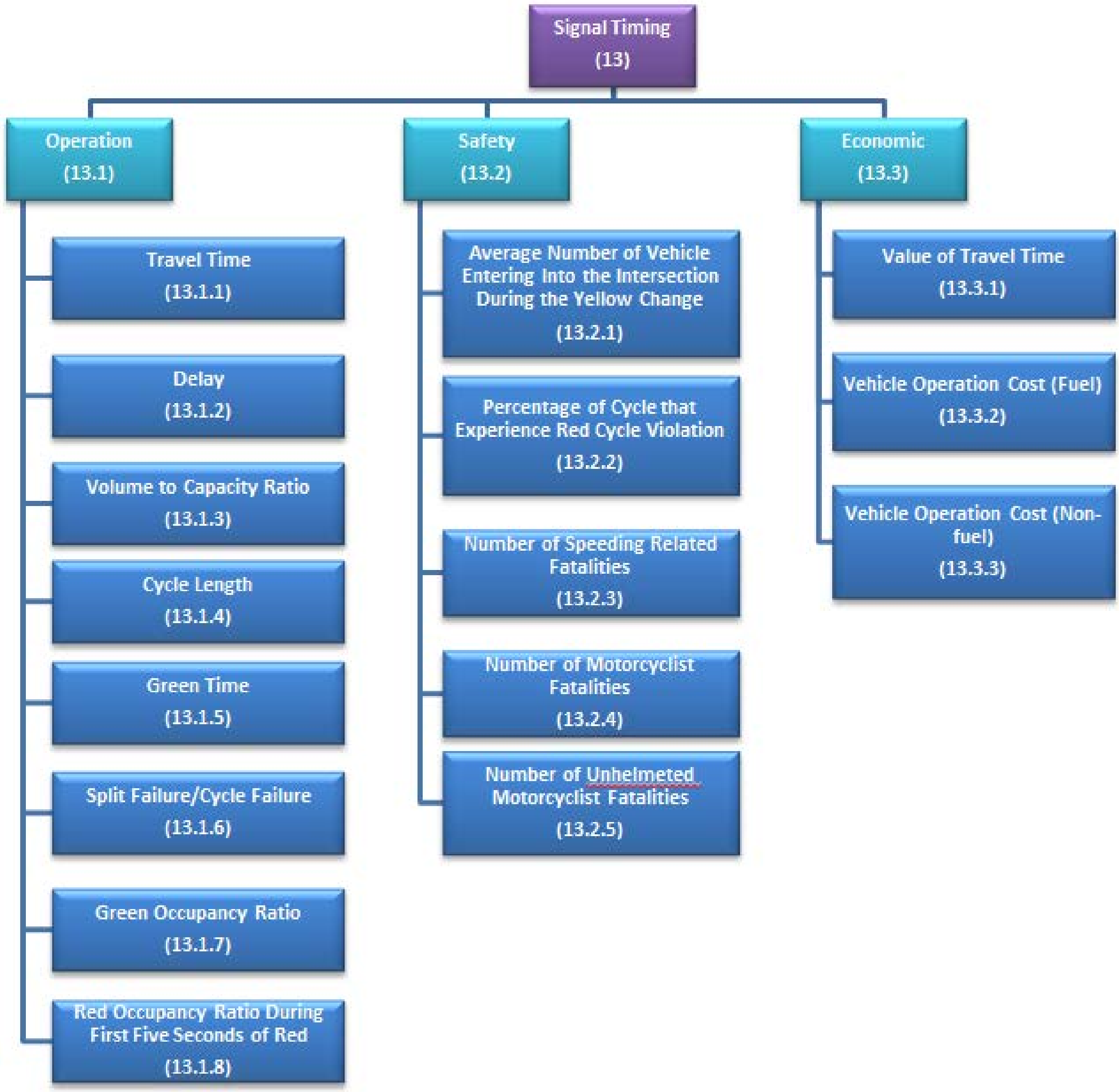

FIGURE 3.14: Signal Timing TSM&O strategy, categories and performance measures

13.1 Operations

13.1.1 Travel Time

13.1.2 Delay

13.1.3 Volume to Capacity Ratio

13.1.4 Cycle Length

13.1.5 Green Time

13.1.6 Split Failure/Cycle Failure

13.1.7 Green Occupancy Ratio

13.1.8 Red Occupancy Ratio During First Five Seconds of Red

- ***Performance Measures for Local Agency Traffic Signals*** **(Grossman and Bullock, 2013)**

(Cycle length, Green time, Volume over capacity, Split failure)

This project, conducted by School of Civil Engineering, Purdue University, concentrates on the implementation of the recommendations from the traffic signal studies of National Cooperative Research Program and Indiana Department of Transportation. A set of several performance measures suitable for implementation by local agencies in near term was identified from a wide range of performance measures. In this study, cycle length, green time, volume over capacity, and split failure were considered as signal timing performance measures. Cycle length as a simple measure in coordinated traffic signal system is a good factor to insure that each pattern cycle length of successive signals is matched. The green time performance measure validates if signal is programed with appropriate green time. Volume over capacity is another efficient performance measure in signal timing techniques to identify if some vehicles need more time or some may have extra time. In order to measure if any particular phase needs more time, split failure is an efficient performance measure in signal system as it specifies the number of split failure occurring in a phase. Another important performance measure suggested by this study is the percentage of phases with pedestrian activation. To confirm adequate split timing without affecting the signal coordination on regular basis, substantial phase usage should be reviewed.

- ***Performance Measures for Traffic Signal Systems: An Outcome-Oriented Approach*** **(Day et al., 2014).**

(Vehicle delay, Travel time, Cycle length, Green time, Green occupancy ratio (GOR), Red occupancy ratio during first five seconds of red (ROR_5))

This report was conducted to assemble a set of performance measures to investigate actual operation of traffic signal systems for all traffic operations. This study summarizes vehicle delay (increased travel time) as the most prominent performance measure of a signal facility. The increase in vehicle travel time is due to traffic control devices, and is also explained in different variations like stopped delay, control delay, approach delay, and estimated approach delay. Other fundamental measures that govern signal timing strategy are cycle length and green time. It is recommended by this study to also measure the effective cycle length and effective green time produced by the controller as a result of phase actuation. Effective green time differs from actual green time as when a vehicle starts to move a few seconds after the beginning of green. To determine the capacity utilization in signal timing techniques, phase termination causes can be analyzed to identify if any phase is exceeding capacity or have capacity to spare. Green occupancy ratio (GOR) and red occupancy ratio during the first five seconds of red (ROR_5) are two performance measures useful to determine the capacity utilization in a signal phase. This study suggests taking GOR and ROR_5 into account in a composite performance measure to get a dominant evaluation of split performance rather than considering them separately. For example, a high value of both GOR and ROR_5 indicates not only the high utilization but also some leftover demands after the green phase.

13.2 Safety

13.2.1 Average Number of Vehicle Entering Into the Intersection During the Yellow Change

13.2.2 Percentage of Cycle that Experience Red Cycle Violation

13.2.3 Number of Speeding Related Fatalities

13.2.4 Number of Motorcyclist Fatalities

13.2.5 Number of Unhelmeted Motorcyclist Fatalities

- ***Potential Measures of Assessing Signal Timing Performance Using Existing Technologies* (Balke and Herrick, 2004).**

(Average number of vehicle entering into the intersection during the yellow change interval, Percentage of cycle experience red cycle violation)

This report; *Potential Measures of Assessing Signal Timing Performance Using Existing Technologies* by Texas Transportation Institution summarized different strategies to collect measures that can be used to evaluate their traffic signal performances. Because an inaccurately programmed signal control can lead to increase crashes, this report identified the measures that affect safety performance of a road due to signal timing strategy. It is suggested that the average number of vehicle entering the intersection during the yellow change interval is an effective measure for traffic safety. If a substantial number of vehicles are entering into the intersection during the yellow change interval, increased extension timers may be needed, as well as increased offset to that intersection. Another prospective measure is percentage of cycles that experience red cycle violations. A considerable number of vehicle in this measure suggests that there is not enough clearance intervals, or adjustments are needed in the dilemma zone, or red light running enforcement program is not working efficiently.

- ***A primer on safety performance measures for the transportation planning process* (Herbel et al., 2009).**

(Number of speeding related fatalities, Number of motorcyclist fatalities, Number of unhelmeted motorcyclist fatalities)

This study reviews current literatures and professional experiences to develop a method for recognizing and applying safety performance measures to transportation planning process. Development of traffic safety is the principal objective of transportation official, since improving safety not only saves lives, but also results in improved mobility, economic development, and overall quality of life. This report analyzes three distinct categories for potential safety performance measures. Core measures are associated with the safety objectives of transportation planning process such as the number of speeding related fatalities, number of motorcyclist fatalities, and number of unhelmeted motorcyclist fatalities.

13.3 Economics

13.3.1 Value of Travel Time

13.3.2 Vehicle Operation Cost (Fuel)

13.3.3 Vehicle Operation Cost (Non-fuel)

- ***The Economic Impact of Traffic Signals and the Effect of Removing Traffic Control Regulations at Road Junctions in the UK* (Siraut and Firth, 2010).**

(Value of travel time)

This report analyzes the economic impacts of removing conventional traffic signal systems at five specific intersections in greater London. The travel time was considered as a performance measure. As travel time was reduced, passengers saw a monetary benefit. The initial study concluded that the economic benefit of removing traffic signal depends on traffic volume, traffic composition, traffic occupancy, pedestrian volume, and time of the day. This research suggests that removing traffic signals results in less travel time; therefore, to have economic benefits, some intersections do not need signal control at different times of the day. Removing traffic signal causes a benefit of around £10,000 a year, to the detriment of over £800,000 a year. This report finally summarized that, although traffic signal is always proven to be economically beneficial, there are some times of the day when greater benefits can be achieved by switching off or removing the traffic signal.

- ***Economic Impact of Traffic Signals GLA Economics* (Greater London Authority, 2009).**

(Value of travel time, Vehicle operation cost (fuel), Vehicle operation cost (non-fuel))

This report on *Economic Impact of Traffic Signals* selected five intersections in London and estimated economic impact of removing traffic signals of each of those intersections.

The economic aspect of intersections can be defined as a combination of monetary cost (fare, petrol costs etc.), time elapsed in the travel, and some other associated attributes like crowing. The results showed significant deviation at individual junctions.

It is generally known that traffic signals are significantly beneficial to road users and pedestrians. However, after modelling and simulating the real life junctions, this study concluded that the elimination of traffic signal results in economic benefit by reducing travel time, vehicle operating cost, and emission. This result was based on five intersections, and just one intersection with a heavy proportion of confliction traffic in a target roundabout showed negative results; the other four benefited economically. The conclusions of this report are exclusive of the benefit or cost due to change in number of crashes (safety).

14 Transit Operations

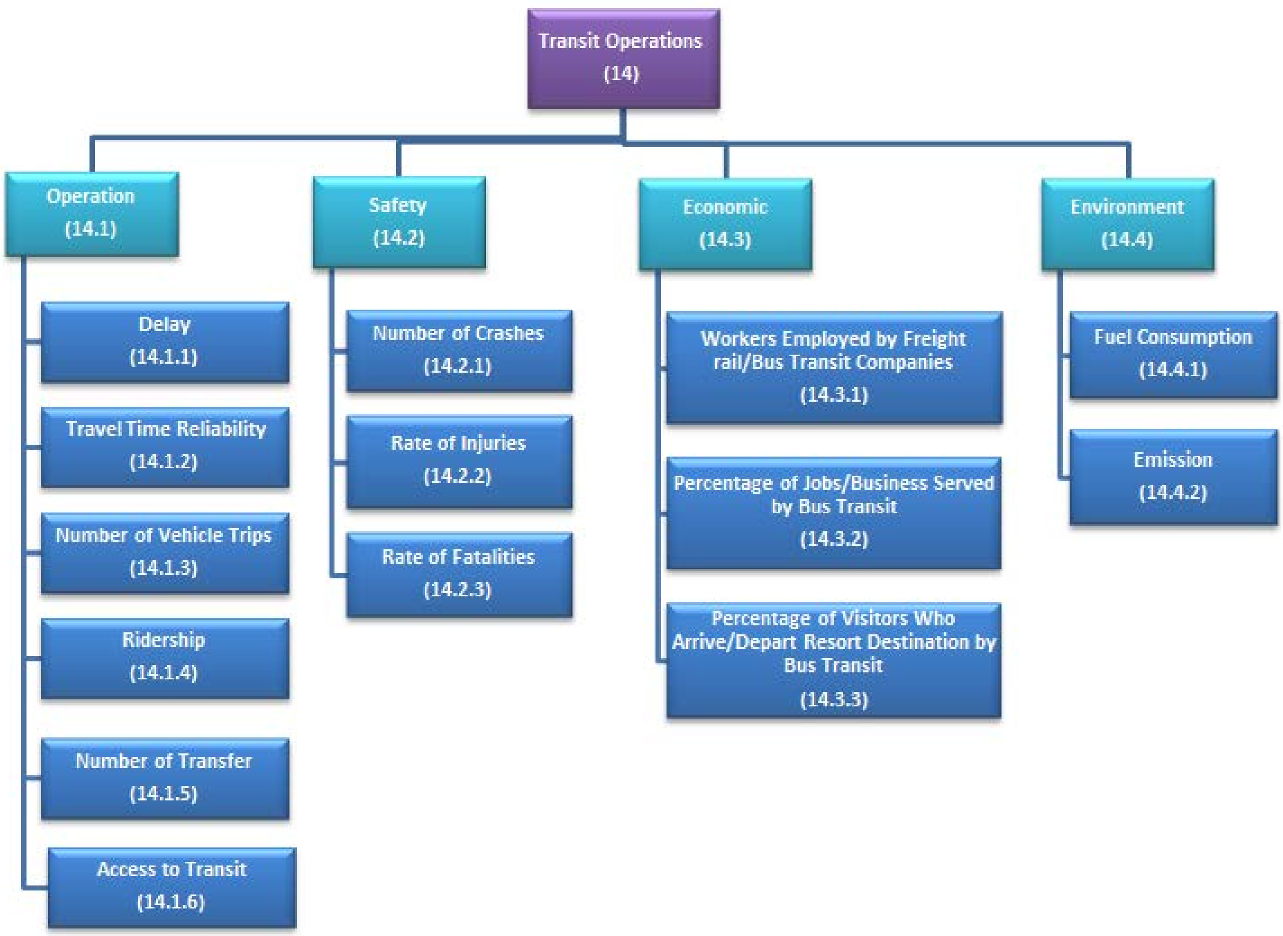

FIGURE 3.15: Transit Operations TSM&O strategy, categories and performance measures

14.1 Operations

14.1.1 Delay

14.1.2 Travel Time Reliability (Percent of bus/rain trips on time)

14.1.3 Number of Vehicle Trips

14.1.4 Ridership (Number of trips taken by public transit)

14.1.5 Number of Transfer

14.1.6 Access to Transit

- ***Establishing a Framework for Transit and Rail Performance Measures*** **(Colorado Department of Transportation, 2012).**

(Number of vehicles trips, Reliability, Number of transfer)

Establishing a Framework for Transit and Rail Performance Measure conducted by Colorado Department of Transportation (CDOT) developed an outline to identify performance measures for transit and rail systems. Performance measures shows how well a specific transportation system is fulfilling its goals and meeting the expectations of thhe transportation network. Mobility is a fundamental requirement of a transit system. The visions for mobility chosen in this reports are to provide transit opportunities to all the population, to ensure seamless connectivity and reduce travel time and travel cost. The candidate measures to evaluate the mobility of transit and rail system, identified by this report are:

- Frequency – Number of bus transit trips daily (on a typical weekday, Saturday, Sunday)
- Frequency – Number of passenger rail trips daily (on a typical weekday, Saturday, Sunday)
- Frequency – Number of bus transit service hours daily (on a typical weekday, Saturday, Sunday)
- Frequency - Number of bus transit service days annually
- Connectivity – Number of timed-transfer stops between intercity bus transit and local bus transit service
- Connectivity – Number of timed-transfer stops between intercity passenger rail and local bus transit service
- Reliability – Percentage of bus transit trips on time
- Reliability – Percentage of passenger rail trips on time
- Percentage of fleet with (Wi-Fi, on-board restrooms, high-back seating)
- Percentage of transit stations with (indoor waiting areas, vending machines, restrooms)
- Percentage of agencies using real-time passenger information systems
- Total bus transit ridership in state (urban, rural)
- Total light-rail transit ridership in state (urban)
- Total passenger rail ridership in state (urban, rural)

- Total transit ridership in state (urban, rural)

The above measures definitively quantify if passengers are comfortable while travelling.

- **Calculation of transit performance measures using smartcard data (Trépanier et al., 2009).**

(Delay)

The Smartcard data system on a transit network helps to improve the toll collection for authorities with a simple ticketing system while ensuring passenger satisfaction. This paper on *Calculation of Transit Performance Measures Using Smartcard Data* measures performance of transit network by using the smartcard system. After determining the supply and demand oriented indicators, this paper summarizes its conclusion with one specific performance measure; *delay*. The results of four months on a specific route indicate that 17.5 percent of the observations were on time, 18.9 percent buses arrived early (avg. 1.6 min) and 63.6 percent buses were late (avg. 3 minutes). Also, delays are higher in inbound direction because traffic friction on the roads is more congested during peak hours in the morning in that area.

- ***Bus rapid transit ridership analysis* (U.S. Department of Transportation, 2005).**

(Ridership)

This report on "Bus Rapid Transit Ridership Analysis" performed by WestStart-CALSTART, California is a survey report on BRT services to demonstrate how the services change ridership levels. The main goal of transit is to move people out of their cars and increase ridership. Therefore, quantifying the ridership of BRT is an important measure to evaluate the performance of BRT system. In Las Vegas, the RTC's "MAX" system is responsible for at least a 35 to 40 percent increase in ridership along its corridor of operation. AC Transit, based in northern California, the Boston based MBTA, and two Los Angeles MTA BRT routes experienced 65.8, 84, 27, and 42 percent increase, respectively, in ridership by switching their limited routes to BRT lines. These changes in ridership shows that BRTs reduce travel time as compared to their previous transportation mode, which encourages passengers to switch to the BRT system.

- **Chicago Metropolitan Agency for Planning (CMAP). http://www.cmap.illinois.gov-/mobility/explore#/**

(Access to Transit, and Ridership)

The Chicago Metropolitan Agency for Planning (CMAP) was created in 2005 as the official regional planning organization for the northeastern Illinois counties. Referred to as the GO TO 2040 plan, transportation system is an important factor for sustaining the region's economy and quality of life. Access to transit is considered a performance measure to evaluate the transit system. Providing access to safe, reliable, and economical public transportation encourages people to use transit more. The access to transit measure is defined as a combination of walkability, connectivity, frequency and proximity. Another measure of evaluating the effectiveness of transit system is ridership. Increasing the ridership of transit system can enhance quality of life, create economic opportunity, and reduce congestion.

14.2 Safety

14.2.1 Number of Crashes (Crashes per VMT, per year, per 1,000 passenger trips)

14.2.2 Rate of Injuries (Number of injuries per 100 million VMT)

14.2.3 Rate of Fatalities (Number of fatalities per 100 million VMT)

- ***Performance measures for public transit mobility management* (Majumdar et al., 2011).**

(Rate of fatalities, Rate of injuries)

Mobility management is a general term that refers to strategies that result in more efficient use of transportation resources. This paper on *Performance Measure for Public Transit Mobility Management* presents a menu of performance measures which can be utilized by the transit authorities to improve the planning, construction, and operations of transit network. Three outcomes were selected to improve the safety of transit systems: Reduction in transportation related fatalities, Reduction in transportation related injuries, and Improved safety experience. The performance measures identified by this study to achieve those three goals are: Rate of transit-related fatalities per 100 million passenger miles traveled, Rate of serious injuries among transit riders per 100 million passenger miles traveled, and Increase in street policies and safe routes to schools.

- ***Establishing a Framework for Transit and Rail Performance Measures* (Colorado Department of Transportation, 2012).**

(Number of incident)

Primary aim of performance measure is to compute if performance of any transportation system is getting better or worse over time, and if the system is performing as expected. *Establishing a Framework for Transit and Rail Performance Measure* conducted by Colorado Department of Transportation (CDOT) provided a framework for categorizing the goals of the transit and rail system in Colorado, and identified several performance measures to evaluate those goals. Safety is a primary goal of transit system, meaning there is no personal harm, property damage, while attaining other goals like mobility, productivity, and etc. This report categorizes three values (Incidents, Facility, and Security) and identified performance measures for each of them.

1. Incidents:
   - Number of incidents (per VMT, per Year, per 1,000 passenger trips) (by severity)
   - Number of incidents at at-grade rail crossings
2. Facility:
   - Percentage of rolling stock with safety features (driver cam, passenger cam, equipment)
   - Percentage of at-grade crossings with active warning protection
3. Security:
   - Percentage of transit bus stops/PNR/transfer points/stations with security features such as lighting, security staff, or CCTV

- Percentage of passenger rail stops/PNR/transfer points/stations with security features such as lighting, security staff, or CCTV
- Percentage of facilities that meet FTA security guidelines

- ***State DOT Public Transportation Performance Measures: State of the Practice and Future Needs* (Grant et al., 2011).**

(Rate of injuries, Rate of fatalities)

This report; *State DOT Public Transportation Performance Measures: State of the Practice and Future Needs* was conducted by the ICF international for National Cooperative Highways Report Program. This study provides comprehensive information about performance management approaches that can be helpful for state DOTs to improve public transportation planning, construction, and operations. This study also summarizes performance measures currently used by different state. For instance, in order to measure safety performances, New Jersey Transit uses rate of injuries involving transit vehicles per million vehicle revenue miles, and Rate of fatalities involving transit vehicles per 100 million vehicle revenue miles. These measures are selected by the authorities because these are trackable over time, have a storytelling potential, and have an available date.

14.3 Economics

14.3.1 Workers Employed by Freight rail/Bus Transit Companies

14.3.2 Percentage of Jobs/Business Served by Bus Transit

14.3.3 Percentage of Visitors Who Arrive/Depart Resort Destination by Bus Transit

- ***Establishing a Framework for Transit and Rail Performance Measures* (Colorado Department of Transportation, 2012).**

(Workers employed, Percentage of jobs, Percentage of visitors)

Though the relationship between economic growth and transportation investment cannot be quantified directly, transportation systems are undoubtedly a prerequisite for economic development. This report on *Establishing a Framework for Transit and Rail Performance Measure* develops certain performance measure for economic development due to transit and rail system. According to this study, economic development can be quantified by the following measures:

- Workers employed by bus transit agencies
- Workers employed by passenger rail agencies
- Number/Percentage of jobs/businesses served by bus transit
- Number/Percentage of jobs/businesses served by passenger rail
- Percentage of visitors who arrive/depart resort destinations by bus transit
- Percentage of visitors who arrive/depart resort destinations by passenger rail
- Percentage of resort visitors who use transit or passenger rail during their stay

14.4 Environment

14.4.1 Fuel Consumption

14.4.2 Emission (Emission of greenhouse gas, NOx, CO2)

- ***Performance measures for public transit mobility management* (Majumdar et al., 2011).**

(Fuel consumption)

Performance Measure for Public Transit Mobility Management, sponsored by Texas Department of Transportation, provides a set of performance measures for public transportation mobility management. One of the prime strategic goals of public transit mobility management is environmental sustainability. In order to evaluate how public transits are affecting the environment, this study suggested a set of outcomes. Moreover, a group of performance measures was introduced to evaluate the outcomes. The associated environmental performance measures are:

- Decreased fuel consumption per vehicle miles traveled, per passenger miles traveled, and per freight ton-mile (net).
- Increased percent of transit vehicles using alternative fuels.
- Increased transit market share for the top 50 urbanized areas.

- ***Bus rapid transit ridership analysis* (U.S. Department of Transportation, 2005).**

(Emission)

The report "Bus Rapid Transit Ridership Analysis" sponsored by Federal Transit Administration, USDOT, describes the effects of BRT on increasing the ridership level and community acceptance of BRT system across the country. In addition, the benefits of increased ridership levels on vehicle miles traveled, emission, and fuel consumption is presented in this report. Survey results show that different BRT systems implemented in several states result in an increase of ridership by 27 to 65 percent. This additional growth in ridership also further provide a quantifiable benefit in the communities by reducing emissions including greenhouse gas emission, NOx, CO2. This report summarizes that BRT saves annual 42800 lb NOx and 20258000 lb of CO2 emission than the private vehicle, which means 45% of NOx and 74% CO2 emissions reduction.

15 Transit Signal Priority

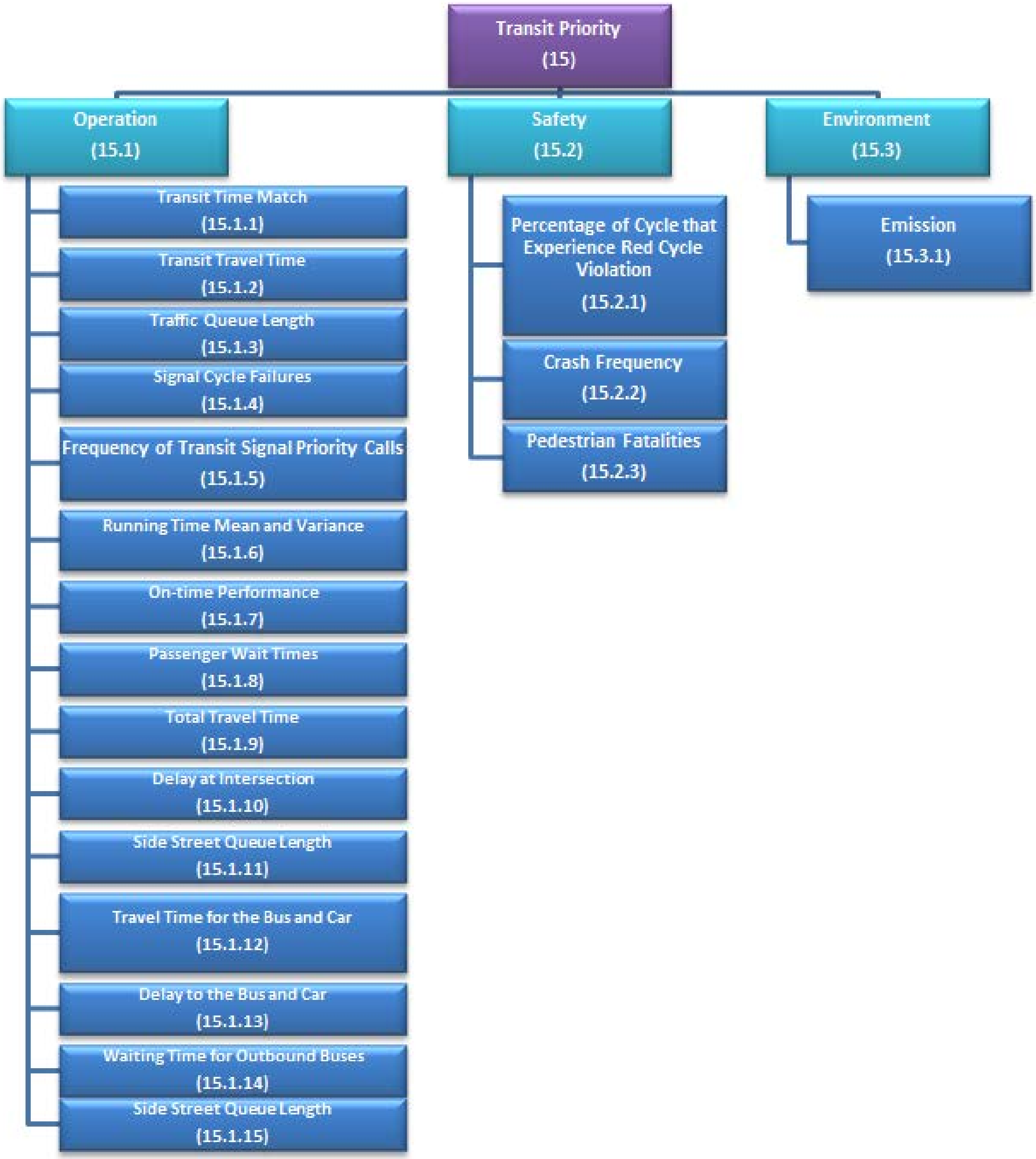

FIGURE 3.16: Transit Signal Priority TSM&O strategy, categories and performance measures

15.1 Operations

15.1.1 Transit Time Match (Transit vehicles adherence to their schedules)

15.1.2 Transit Travel Time

15.1.3 Traffic Queue Length

15.1.4 Signal Cycle Failures

15.1.5 Frequency of Transit Signal Priority Calls

15.1.6 Running Time Mean and Variance

15.1.7 On-time Performance

15.1.8 Passenger Wait Times

15.1.9 Total Travel Time

15.1.10 Delay at Intersection

15.1.11 Side Street Queue Length

15.1.12 Travel Time for the Bus and Car

15.1.13 Delay to the Bus and Car

15.1.14 Waiting Time for Outbound Buses

15.1.15 Side Street Queue Length

- ***Comprehensive evaluation of transit signal priority system impacts using field observed traffic data*** **(Washington State Department of Transportation, 2008).**

(Transit time match, Transit travel time, Traffic queue length, Signal cycle failures, Frequency of transit signal priority calls)

This research was conducted by Washington State Department of Transportation to improve the level of service for Community Transit buses. The simulation models were built and calibrated to evaluate the effectiveness of the Transit Signal Priority (TSP) system. The measures of effectiveness were separated into two categories: primary and secondary. Transit time match, transit travel time, traffic queue length, signal cycle failures, and frequency of TSP calls were chosen as the primary measures of effectiveness. These measures, which addressed the major concerns of TSP, were calculated directly using field observed data. The secondary category, which was calculated using microscopic simulation, includes the average person delay, vehicle delays, and stops.

- ***Analysis of Transit Signal Priority Using Archived TriMet Bus Dispatch System Data Final Report*** **(Kimpel et al., 2005).**

(Running times mean and variance, On-time performance (OTP), Scheduling benefits, Passenger wait times)

Transit Signal Priority is one the strategies to reduce running time delay. This study used the data derived from the TriMet Bus Dispatch System for comprehensively analyzing changes in bus performance following TSP implementation. The mean and variance of running times, changes in on-time performance (OTP), scheduling benefits, and passenger wait times were considered as performance measures. In addition, to consider the effect of the after TSP implementation period on actual running times, a regression model was conducted.

- ***Evaluating the Transit Signal Priority Impacts along the US 1 Corridor in Northern Verginia*** **(Kamdar, 2004).**

(Total travel time, Delay at intersection, Side street queue length)

In this study, the objective was to test the impact of green phase extension priority strategies on transit system. The VISSIM microsimulation was used to model 26 intersections along U.S. 1. Various quantitative and qualitative measures of effectiveness were chosen in this study: Bus service reliability, bus efficiency, and bus control delay. Performance measures to evaluate the transit services were total travel time, delay at intersection, and side street queue length. The results were reported as a 4% reduction in transit travel time, 5-13% control delay improvement, and up to 1.23% increase in maximum queue length.

- ***Improving Transportation Mobility, Safety, and Efficiency: Guidelines for Planning and Deploying Traffic Signal Priority Strategies*** **(Collura et al., 2008).**

(Travel time for the bus and car, Delay to the bus and car, Waiting time for outbound buses, Side street queue length)

This study was conducted to evaluate and analyze use of traffic signal systems and technologies to implement transit signal priority strategies for Vermont Agency on Transportation (VAOT), regional agencies, and local jurisdictions in the Vermont State. VISSIM was used to simulate alternative transit priority strategies along two major bus routes: 1) the Old North End Loop in downtown Burlington, and 2) the bus route along Route 15. Four major categories were defined to evaluate the simulation analysis: 1) travel time for the bus and car; 2) delay to the bus and car; 3) waiting time for outbound buses; and 4) side street queue length. Beside the performance measures, this study indicated a set of anticipated consequences of alternative transit priority strategies which should be considered pre-deployment. Among those consequences, traffic flow, pedestrian safety, and economic analysis were highly recommended.

15.2 Safety

15.2.1 Percentage of Cycle that Experience Red Cycle Violation

15.2.2 Crash Frequency

15.2.3 Pedestrian Fatalities

- ***Evaluating the Transit Signal Priority Impacts along the US 1 Corridor in Northern Verginia*** **(Kamdar, 2004).**

(Red light running, Crash frequency)

In order to increase the efficiency of transit systems, many strategies have been recommended. One the most effective ways to improve the transit service reliability and efficiency is implementing Transit Signal Priority. This research in form of a Master's thesis focuses on the impacts of transit signal priority in the U.S.1 corridor in Fairfax County. Safety is one of the traffic aspects which influenced by transit signal priority at intersections. In this research, safety was measured by red light running and crash frequency. Transit signal priority was simulated using VISSIM considering a ten second green extension priority strategy.

- ***Planning and deploying transit signal priority in small and medium-sized cities: Burlington, Vermont, case study*** **(Vlachou et al. 2010).**

(Pedestrian fatalities)

Transit Signal Priority is introduced as one of the strategies to increase the transit system reliability and efficiency. This study was conducted as a Planning and Deploying Transit Signal Priority guideline in Small and Medium-Sized Cities. One of the primary objectives of this research was applying a micro-simulation model, VISSIM, to assess transit priority impacts. In order to assess the safety impacts of transit signal priority, this study recommended the pedestrian fatalities as the most potential impact of this strategy on safety.

15.3 Environment

15.3.1 Emission (Emission of total organic gases, carbon monoxide, particulate matter and nitrogen oxides)

- ***A Transit Signal Priority Impact Assessment Methodology—Greater Reliance on Simulation*** **(Dale et al., 1999).**

(Vehicle emissions)

In this study, the transit signal priority impact assessment consists of two primary components: (1) field study and (2) simulation. Real-world assessment of transit signal priority impacts was conducted through field study. However, the evaluation of various transit signal priority strategies without implementing before and after study in filed was performed with simulation. Vehicle emissions were used to measure the effectiveness of transit signal priority on air quality and environment. Since transit signal priority strategies is not expected to impact travel mode decisions short-term, this impact is derived from the possible long-term shift of current drivers to transit users.

16 Travel Demand Management

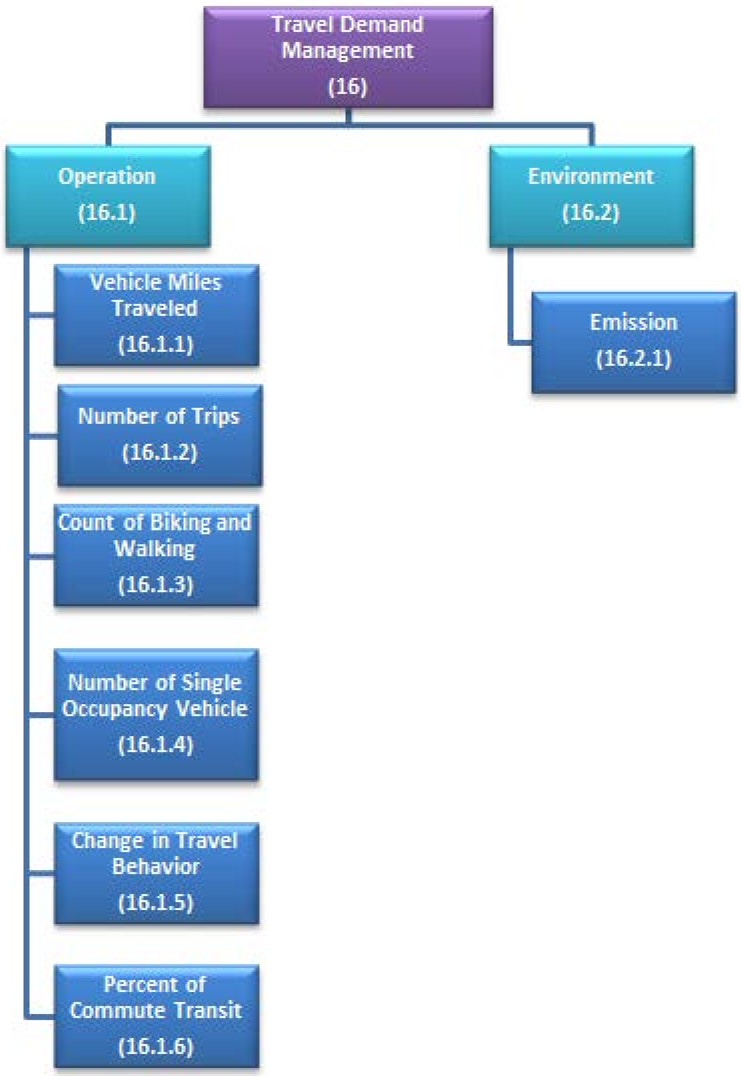

FIGURE 3.17: Travel Demand Management TSM&O strategy, categories and performance measures

16.1 Operations

16.1.1 Vehicle Miles Traveled

16.1.2 Number of Trips

16.1.3 Count of Biking and Walking

16.1.4 Number of Single Occupancy Vehicle

16.1.5 Change in Travel Behavior

16.1.6 Percent of Commute Transit

- ***A Framework for Monitoring the Performance of Demand Management and Vehicle Miles Traveled (VMT) Reduction Activities*** **(Hallenbeck et al., 2013).**

(Vehicle miles traveled, Count of biking and walking, Percent of commute trips)

The report *A Framework for Monitoring the Performance of Demand Management and Vehicle Miles Traveled (VMT) Reduction Activities* conducted by Washington State Transportation Centre (TRAC) provides an excellent framework to support performance monitoring for demand management related to vehicle miles traveled (VMT). Demand management includes all the strategies that encourage the public to travel in such a way that minimizes their impact on others. Recommended measures to evaluate the effect of travel demand management on the transportation network system are statewide VMT, light-duty vehicle VMT, count of biking and walking, and percent of commute trips.

- ***Travel Demand Model Development and Application Guidelines*** **(Oregon Department of Transportation, 1994).**

(Number of trips, Vehicle miles travelled)

Transportation demand management (TDM) includes different strategies to maximize the people moving capability of transportation system by increasing the number of person in a vehicle or by influencing the time or need to travel. By influencing travel behavior through the implementation of TDM strategies, congestion can be reduced or managed for a long time. Some TDM strategies in different communities in US are flexible time for workers, alternate work schedule, compressed work week, carpooling, car-sharing, bicycling, walking, express bus service, traditional transit, and ramp metering. All these strategies have a significant role in improving operational activity of transportation network by reducing number of trips and vehicle miles traveled (VMT).

- ***Transportation Demand Management Plans for Development*** **(Oregon Department of Transportation, 2013).**

(VMT, Counts of biking and walking, Percentage of commute transit)

Transportation demand management (TDM) is the use of strategies and policies to motivate people to change their travel behavior to shift modes, make fewer trips, and drive more efficiently. TDM strategies have been proven to be more efficient than simply building roads to reduce traffic congestion, save time and cost, and lower healthcare costs. Some of the most common TDM strategies are advertising prominent web pages, transit pass programs, ride matching services, telework opportunities, individualized marketing, and active and safe routes to school programs. The report *Improving Travel Options with Transportation Demand Management (TDM)* summarizes the effectiveness of TDM with several real life examples. In the greater Toronto and Hamilton area, smart commute initiatives were implemented in 2004, which resulted reduction of 45 million vehicle miles traveled (VMT).

- ***Transportation Demand Management Plans for Development*** **(Oregon Department of Transportation, 2013).**

(Vehicle miles travelled, Number of single occupancy vehicle)

Transportation demand management (TDM) is a set of strategies to reduce vehicle miles travelled (VMT) and single occupancy vehicle (SOV) of a specific site over time. It may include priced parking, universal transit pass, shuttle service, vanpooling, and car-sharing. The report *Transportation Demand Management (TDM) Plans for Development* conducted by Oregon Department of Transportation illustrates the benefit of TDM through several examples and case studies. One of the most important measure by which the effect of different TDM strategies can be evaluated is vehicle miles travelled (VMT) and number SOV trips. Washington State succeeded in reducing their SOV trip rate by 2.8% that resulted a 2.6% VMT reduction from 2007-2009 by implementing community trip reduction plan. Therefore, this report concluded that implementing proper TDM plans can significantly impact the overall improvement of the transportation network of any specific area.

- **TDM Encyclopedia, Victoria Institute of Transportation, http://www.vtpi.org/tdm/tdm12.htm.**

(Change in traveler behavior)

The Victoria Transportation Institute developed an online encyclopedia on transportation demand management. The Online TDM Encyclopedia is the world’s most comprehensive information resource concerning innovative transportation management strategies. It describes dozens of Transportation Demand Management (TDM) strategies and contains information on TDM planning, evaluation, and implementation. TDM refers to a set of various strategies that change travel behavior to increase transportation system efficiency. TDM strategies move toward the change of travel behavior to choose more efficient travel patterns, such as a shift from peak- to off-peak periods, from automobile to alternative modes, and from dispersed to closer destinations.

16.2 Environment

16.2.1 Emission (Emission of total organic gases, carbon monoxide, particulate matter and nitrogen oxides/ Emission of greenhouse gases)

- ***Travel, emissions, and welfare effects of travel demand management measures* (Rodier and Johnston, 1997).**

(Emission)

This study evaluates the effect of various scenarios TDM on travel, emissions, and welfare in Sacramento, California region. Different scenarios are developed based on combination of the land-use intensification measures, pricing policies, high occupancy vehicle lane, and light-rail transit expansion. To quantify the emission, the California DOT's Direct Travel Impact Model 2 (DTIM2) and California Air Resources Board's EMFAC7F model were used. The daily emissions projections for the year 2015 scenarios in the Sacramento region resulted in the greatest reduction in emission over the no-build scenario. The pricing and HOV scenario increased the reduction of total organic gases (TOG), carbon monoxide (CO) and particulate matter (PM) and decreased the reduction in nitrogen oxides (NO_x) over other pricing scenario. Pricing and HOV lanes reduce TOG by 13%, CO by 10%, NOx by 6% and PM by 9%.

- ***Effects of Travel Reduction and Efficient Driving on Transportation: Energy Use and Greenhouse Gas Emissions* (Porter et al., 2013).**

(Emission)

Numerous transportation strategies are directed at reducing energy use and greenhouse gas (GHG) emissions by changing the behavior of individual drivers or travelers. Active demand management is one such strategy which can include road pricing, parking pricing, and dedicated lanes for high occupancy vehicle. This paper estimated impact of individual strategies on surface transportation energy use and GHG emissions ranges from less than 1% to a few percent points. Pricing that applies to all or a large fraction of travel has the potential to be one of the most effective strategies, if it can be implemented in a way that is acceptable to the general public.

17 Freight

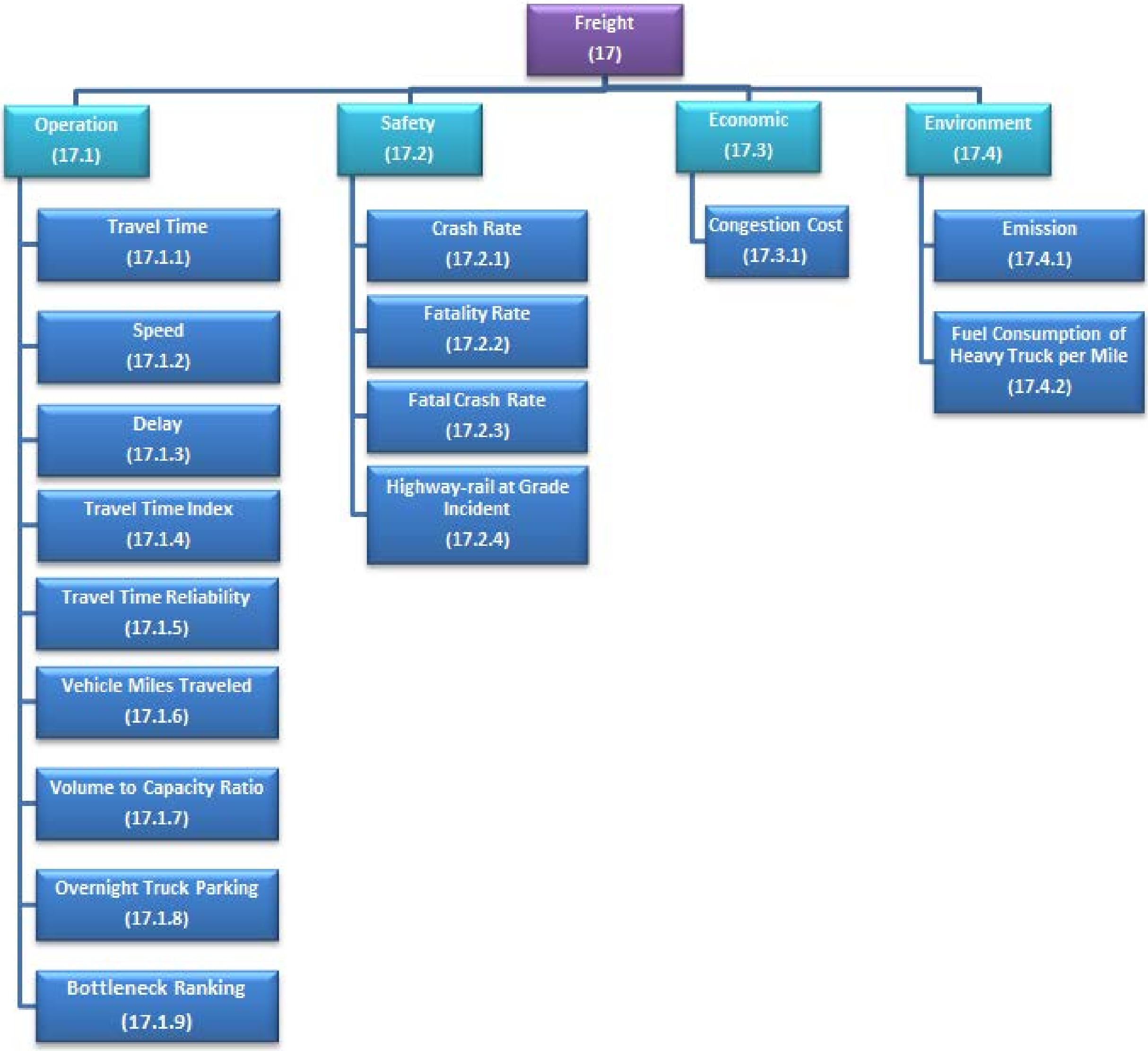

FIGURE 3.18: Freight TSM&O strategy, categories and performance measures

17.1 Operations

17.1.1 Travel Time

17.1.2 Speed

17.1.3 Delay

17.1.4 Travel Time Index (Ratio of peak period travel time and free flow travel time)

17.1.5 Travel Time Reliability (Daily travel time variation)

17.1.6 Vehicle Miles Traveled

17.1.7 Volume to Capacity Ratio

17.1.8 Overnight Truck Parking

17.1.9 Bottleneck Ranking

- ***Freight Performance Measures Guide* (Schofield et al., 2006).**

(Travel time, Delay)

The guide on *Freight Performance Measures* (FPMs) conducted by the Texas Department of Transportation was developed to describe the freight performance measures to evaluate the goals and objectives decided by the transportation agencies. Mobility and reliability are the two main issues which were described by FPMs in this guidebook, and were evaluated using travel time and delay as performance measures.

- ***Freight Performance Measures: Approach Analysis* (McMullen and Monsere, 2010).**

(Travel time index, Vehicle miles travelled (VMT), Delay, Volume to capacity ratio)

Freight performance measures are indicators of whether determined goals are achieved in a freight transportation system. The study *Freight Performance Measures: Approach Analysis* conducted by Oregon Department of Transportation reviews the state-of-the-arts freight performance measures. The freight performance measures regarding mobility of highway used by state department of transportations are summarized in this paper, and the most common are:

- Travel Time Index
- Vehicle Miles Travelled
- Average Daily Hours of Delay Time
- Travel Time Reliability
- Volume to Capacity Ratio
- Percent of Urban Miles Congested
- Percent of Rural Miles Congested

- ***Freight System Performance Measurement for the Tampa Bay Region* (Florida Department of Transportation, 2014).**

(Vehicle miles travelled (VMT), Volume to capacity ratio, Travel time index, Delay)

Research on freight performance measures have developed more leisurely than the other sector due to lack of a clear federal mandate. *Freight System Performance Measures for the Tampa Bay Region* presents a set of performance measures to help achieve these goals for freight movement. Mobility orientated performance measures recommended by this paper are:

- Vehicle Miles Travelled (VMT)
- Volume to Capacity ratio
- Travel Time and Reliability
- Delay per year

All those performance measure then assessed based on five criteria: understandability, usefulness, forecast potential, data quality, and ease of data collection. For example, volume to capacity ratio scored moderately in understandability, usefulness, data quality, and ease of data collection, but it has a very high impact on predicting future conditions.

- ***Performance Measures for Freight Transportation* (Transportation Research Board, 2011).**

(Speed, Travel time reliability)

The freight transportation network is a complex and dynamic network for public and private sectors involving all modes of transportation- truck, rail, waterway, air, pipelines, etc. The report *Performance Measures for Freight Transportation* by National Cooperative Freight Research Program (NCFRP) summarizes a comprehensive set of performance measures for freight transportation networks which are important in evaluating existing conditions, identifying problems, prioritizing the actions to resolve the problems, and measuring the effectiveness of those actions. In order to evaluate the mobility of freight transportation networks, this report identified two major performance measures which are Highway Speed and Highway Reliability. It is observed that average speed is higher in rural areas and lower in large, urban regions. In addition to average speed, percent of segment of the highway with average speed less than the free flow gives the reliability measure. Reliability refers to the predictability of highway speed and travel time and is highly valued to predict the estimated shipment time.

- ***Maryland state highway mobility report – 2nd edition* (O'Malley and Brown, 2013).**

(Overnight truck parking)

The Maryland State Highway Mobility Report highlighted the major success, challenges, and strategies implemented to improve the transportation services. As a part of the freight implementation plan to enhance the safety and efficiently movement of commercial vehicles freight, the expansion of truck parking at Howard County was initiated in 2012. This report also discusses the congestion points and lack of overnight parking across the Maryland truck route network, which directly impacts the mobility and safety of the network. In 2012, a survey of the

Maryland Truck Route system observed over 600 trucks were parking on the roadways and ramps directly on or near the roadways. Therefore, the estimation of the overnight truck parking spaces can be used as a measure to find out how the freight mobility strategies are functioning.

- ***Using GPS truck data to identify and rank bottlenecks in Washington State*** **(McCormack et al., 2011).**

(Bottleneck ranking)

One of the measures to evaluate the performance of freight network is bottleneck rank of various segments in network. This study conducted the bottleneck ranking using GPS truck data from commercial, in-vehicle, and truck fleet management systems. In this study, the bottleneck ranking was conducted based on a range of measures such as average segment travel speed, geographical location, and the segment's Freight Goods Transportation System (FGTS) category.

17.2 Safety

17.2.1 Crash Rate (Crashes per 100 million VMT)

17.2.2 Fatality Rate (Fatalities per 100 million VMT)

17.2.3 Fatal Crash Rate (Fatal crashes per 100 million VMT)

17.2.4 Highway-rail at Grade Incident

- ***Freight Performance Measures: Approach Analysis*** **(McMullen and Monsere, 2010).**

(Fatality rate, Crash rate, Crash rate)

The study *Freight Performance Measures: Approach Analysis* conducted by Oregon Department of Transportation is based on past and present research in freight performance measurement, and it discusses recent literature on the development of this measures. Safety is the most common goal undertaken by the agencies, and fatality rate (fatalities per 100 million vehicle miles travelled) is the most frequently used performance measure to evaluate the safety goals. Other performance measures like crash rates, and personal injury rate were also used by state department of transportation to assess the safety.

- ***Freight System Performance Measurement for the Tampa Bay Region*** **(Florida Department of Transportation, 2014).**

(Crash rate, Fatality rate)

The purpose of the study *Freight System Performance Measures for the Tampa Bay Region* is to provide information and background on freight performance measures used by several state departments of transportation. This report also recommends performance measures for the Tampa bay region. Safety is one of the most important goals in freight system. To quantify safety, this study recommends several performances measures. All the measures were identified based on understandability, usefulness, forecast potential, and data quality. Recommended performance measures are:

- Truck crashes per truck VMT
- Percent of truck crashes involving injury
- Percent of truck crashes involving fatalities
- Truck crashes injuries
- Truck crashes fatalities

- ***Performance Measures for Freight Transportation* (Transportation Research Board, 2011).**

(Fatal crash rates, Highway-rail at grade incident)

The freight transportation network is a complex and dynamic network for public and private sectors involving all modes of transportation. The report *Performance Measures for Freight Transportation* by National Cooperative Freight Research Program (NCFRP) summarizes a comprehensive set of performance measures for freight transportation network, which are important when evaluating existing condition, identifying problems, prioritizing the actions to resolve these problems, and measure the effectiveness of these actions. Two major measures to evaluate the safety factor of freight transportation are *Fatal Crash Rates* and *Highway-Rail at grade incident*. Large truck fatal crash rate has declined in last decade. In 1979 large truck crash rate was 5.21 which decreased significantly in 2007 at 1.85. Data suggest that Highway-Rail at grade incident has also decreased in US since 1989.

- ***Development of Performance Measurement for Freight Transportation* (Kelle et al., 2014).**

(Fatality rate, Crash rate)

Freight transportation is the physical way to transfer commodities and goods from one place to another by different modes of transportation. The presentation on *Development of Performance measures for Freight Transportation* establishes different measures affecting safety, mobility, and environmental aspects of freight transportation.
Safety performance measures identified by USDOT in 2011 are as below:

- Passenger vehicle occupant highway fatality rate per 100 million passenger vehicle miles traveled (VMT);
- Large truck and bus fatality rate per 100 million total VMT;
- Motorcyclist fatality rate per 100,000 motorcycle registrations;
- Non-occupant fatality rate per 100million VMT;
- Number of commercial air carrier fatalities per 100 million persons onboard;
- Fatal crashes per 100,000 flight hours in general aviation;
- Rail-related crashes and incidents per million train miles;
- Transit fatalities per 100 million passenger-miles traveled;
- Number of natural gas and hazardous liquid pipeline incidents with death or major injury; and

- Number of hazardous materials transportation incidents with death or major injury.

17.3 Economics

17.3.1 Congestion Cost

- ***Maryland state highway mobility report – 2nd edition* (O'Malley and Brown, 2013).**

(Congestion cost)

The Maryland State Highway Mobility Report summarizes the mobility related efforts of the Maryland State Highway Administration (SHA) in 2012 and highlights successes, challenges, and strategies being utilized in transportation services improvement. The 2012 Annual Urban Mobility report of Maryland SHA recognizes congestion costs related to trucking operations. Congestion has a major impact on trucking operations as well as automobile traffic. Costs associated with delays of freight arriving on time and extra fuel costs are more significant to truckers than motorists. The Washington DC metropolitan area was ranked number eight nationwide of total annual delay for trucks, which amounted to 8.6 million hours of delay. It was estimated that in the Maryland Truck Route System, a total of $172.4 million was caused by freight congestion in 2012.

17.4 Environment

17.4.1 Emission (tons/day of particulate matter, nitrogen oxides, volatile organic compounds, ozone and greenhouse gases)

17.4.2 Fuel Consumption of Heavy Truck per Mile

- ***Freight Performance Measures: Approach Analysis* (McMullen and Monsere, 2010).**

(Emission, Fuel consumption of heavy truck per mile)

Performance measurement has become an integral part of the business of any state department of transportation. The paper on *Freight Performance Measures: Approach Analysis*, conducted by Oregon Department of Transportation, is based on the past and present research in freight performance measurement. It also discusses the recent literature on the development these measures. Most common environmental measures used by state departments of transportations regarding freight transportation network are:

- Volatile Organic Compounds (tons/day)
- Nitrous Oxides (tons/day)
- Carbon Monoxide (tons/day)
- Particulate Matter (tons/day)
- Number of Gallons Fuels Consumed
- Fuel usage per capita

- ***Freight System Performance Measurement for the Tampa Bay Region* (Florida Department of Transportation, 2014).**

(Emission)

Performance measures ultimately influence transportation project selection for agencies. *Freight System Performance Measures for the Tampa Bay Region* laid out several potential performance measures for freight system performance in Tampa Bay Region. This study recommends two environmental measures: Freight-related criteria pollutant emissions, and Freight-related greenhouse gas emissions. These two measures are assessed based on some criteria like ease of data collection, usefulness, and understandability. Required data to quantify pollutant and greenhouse gas emission are hard to collect, but they both have very good forecasting potentials.

- ***Performance Measures for Freight Transportation* (Transportation Research Board, 2011).**

(Emission)

The objective of the research *Performance Measures for Freight Transportation* is to establish a set of measures to evaluate the performance of U.S. freight transportation network. The following is the set of environmental measures recommended by this study:

- Particulate matter (PM)
- Oxides of nitrogen (NOx)
- Volatile organic compounds (VOCs)
- Ozone
- Greenhouse gas emissions (GHE)

Emission of these pollutants has declined since 2002 due to stricter emission standards, cleaner engines and fuel mandates, and voluntary industry effort to reduce fuel consumption. As of October 10, 2007, air-quality data show that about 144 million people live in areas that violate air-quality standards for ground-level ozone. These pollutants contribute to serious public health problems that include premature mortality, aggravation of respiratory, cardiovascular disease, aggravation of existing asthma, acute respiratory symptoms, and chronic bronchitis.

18 Road Weather Management

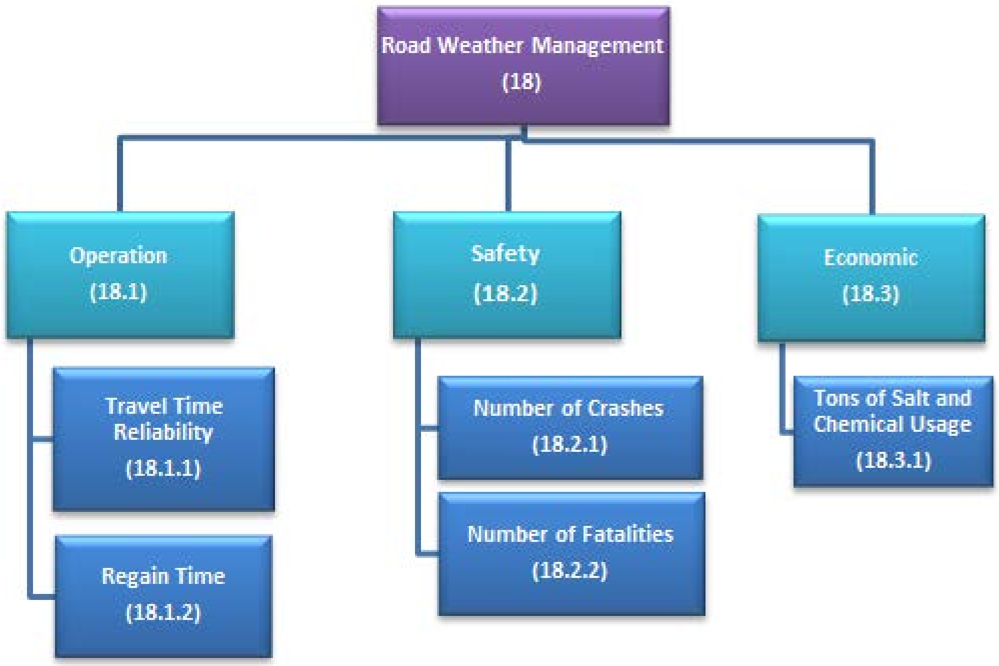

FIGURE 3.19: Road Weather Management TSM&O strategy, categories and performance measures

18.1 Operations

18.1.1 Travel Time Reliability (Variation in travel time)

18.1.2 Regain Time (Time needed for returning to normal traffic operation after a weather emergency)

- ***Road Weather Management Performance Measures–2012 Update* (Gopalakrishna, 2013).**

(Travel time reliability)

Road Weather Management Program (RWMP) piloted a study in 2007 to define eleven performance measures that would cause the Federal Highway Administration (FHWA) evaluate their desired goals. This report on "Road Weather Management Performance Measures" is a follow-up to appraise those performance measures. One of the objectives of RWMP was to improve overall system performance during weather events by increasing travel time reliability or decreasing variability due to road weather management strategies. Travel time reliability means how travel time varies over time. Higher variation suggests a lower level of reliability. Travel time reliability has more impact than average travel time to the travelers. This measure is calculated from the frequency distribution of the travel times gathered over a specific period. Analysis shows that travel time reliability decreases in bad weather, meaning greater variation in travel time is observed in bad weather compared to good weather.

- ***Regional Operations Forum Road Weather Management*** **(Transportation Research Board, 2014).**

(Regain time)

The objective of the presentation on "Regional Operation Forum Road Weather Management" is to offer consciousness of the principles and elements related to modern road weather management and show how to implement those elements. One of the performance measure defined by this presentation is regain time, which is used by most DOTs. Regain time is the time needed for any transportation system to return to normal seasonal condition after a weather emergency. For the winters of 2009 to 2012, the Michigan DOT has collected storm start times and end times along with other information about the intensity and temperatures during the storm. The data are then used to illustrate regain time, which is the time needed after a winter storm event until vehicle speeds return to normal operating speeds.

- ***Estimating Winter Weather Road Restoration Time Using Outsourced Traffic Data: Three Case Studies in Maryland*** **(Sharifi et al., 2014).**

(Regain time)

The objective of this report is to calculate winter weather road restoration performance measure, regain time, by using speed and travel time data collected on I-95. The most common performance measure for winter weather operations is regain time, which is used by most of the DOTs. This performance measure can be calculated with improvement in technology and traffic data. In the MnDOT, loop detectors were used to collect speed, flow, and density when traffic patterns returns to normal after bad weather. The Michigan DOT uses a different approach to find regain time in winter weather events. The starting and ending time of the winter storm is determined by operations personnel. Traffic data is collected based on 10 minute average data from RITIS. Normal traffic operation is considered when average speed rises to within 5 mph of average historical speed for at least one hour. The primary goal of the Michigan DOT is to regain normal speed in 2hours or less, 80% of the time for winter weather events.

18.2 Safety

18.2.1 Number of Crashes

18.2.2 Number of Fatalities

- ***Seasons of achievement. Accomplishments of the road weather management program*** **(Pisano, 2010).**

(Number of crashes)

Road Weather Management Program is a part of the Federal Highway Administration's Office of Operation and works in combination with the Intelligent Transportation Systems (ITS). This program addresses road weather challenges through research, technology development, and community outreach to gain a greater understanding of the impact weather has on roadways and through the promotion of strategies and tools that mitigate those impacts-anytime and anywhere. Decreasing the number of crashes in inclement weather is one of the biggest challenges of the Road Weather Management Program. In northern Idaho, implementation of an anti-icing program resulted in 83 percent decline in winter crash frequency. North Carolina reported a 39 percent crash reduction from using the wet pavement warning systems. Utilizing the automatic bridge anti-icing system in Utah reduced crashes by 64 percent. In Tennessee, installation of a fog warning system has reduced fog-related crashes down to one from the 200 crashes from the previous 20-year period. It can be concluded that one of the primary goals of RWMP is to reduce traffic-related crashes due to improved road weather advisory, control, and treatment strategies.

- ***Guidelines for Disseminating Road Weather Advisory & Control Information*** **(Lichty et al., 2012).**

(Number of crashes, Number of fatalities)

This is a guideline for transportation officials to develop road weather messages that support traveler information needs before and during trips. Proper information helps travelers make safe and intelligent travel decisions during bad weather. There is a specific guideline in this paper on how safety impacts for weather events can affect travelers' safety, crash risk, and convenience or schedules. Crash data analysis provides a partial indication of which conditions require information. For example, low traction and low visibility play a major role in crashes and fatalities.

18.3 Economics

18.3.1 Tons of Salt and Chemical Usage

- ***Road Weather Management Performance Measures–2012 Update*** **(Gopalakrishna et al., 2013).**

(Tons of salt and chemical usage)

Road Weather Management Program (RWMP) piloted a study in 2007 to define 11 performance measures that would make Federal Highway Administration (FHWA) to evaluate their desired goals and in 2010. This report on "Road Weather Management Performance Measures" is a follow-up to appraise those performance measures. One of the objectives of RWMP was to improve the overall system performance during weather events by reducing the tons of salts or chemical usage. It is estimated that in 2011, 19.6 million tons of salt were used nationwide to deice during winter. Implementation of a Maintenance Decision Support System (MDSS) like deicing, and anti-icing methods in Indiana showed significant cost reduction of $12 million for salt usage in winter season. However management of salt use from a cost-saving standpoint has started to become as a priority for agencies, but methods to evaluate their performance across the winter is rare.

Chapter 4 - Review of Relevant MAP-21 Efforts

4.1 Problems and Opportunities for Common TSM&O-Specific Performance Measures

This section focuses on the performance measures used to evaluate TSM&O strategies as defined in previous task. A list of performance measures were retrieved from various research and studies, including documentation of current agency practices, system performance statistics, and DOTs' research and implementation activities. The purpose of this task is to provide additional information on performance measures in tabular form. In order to facilitate the use of performance measures by practitioners, selected measures are categorized in different perspectives, and presented in a series of tables and matrices.

Categorization Based on Various Transportation Perspectives

At this step, all the TSM&O performance measures were categorized under various transportation aspects, including Operation, Safety, Economic, and Environment. This categorization helps practitioners find out the proper performance measures to conform evaluation perspectives. Table 4.1 presents the various performance aspects, and related measures to evaluate TSM&O strategies. Each individual performance measure is included in one or more of these four categories and presented in a tabular form. For example, in order to evaluate the effects of Access Management strategy from a traffic safety perspective, various measures were found in the literature such as Crash Rate, Number of Crashes, Number of Injury and Fatalities, Number of Property Damages, and Time-to-Collision. This table will help the practitioner to quickly retrieve proper performance measures to evaluate any TSM&O strategies with respect to objected perspective.

Table 4.1: Performance measures based on operation, safety, economic and environmental aspect of different TSM&O strategies

TSM&O Strategy	Sub-category	Performance Measure
Access Management	Operation	Travel Time
		Speed

		Delay
		Queue Length
	Safety	Crash Rate (Crash per million VMT)
		Number of Crashes
		Number of Injury and Fatalities
		Number of Property Damages (Number of property damages only (PDO))
		Time-to-Collision (Time takes for a vehicle to collide into another if they continue at the same speed without trying to avoid each other)
	Economic	Business Turnover
		Commercial Land Values
		Property Value
Active Parking Management	Operation	Travel Time
		Duration of Vehicle Trips
		Number of Double Parking
		Parking Space Availability (Percent of spaces occupied)
Active Traffic Management (ATM)	Operation	Travel Time
		Speed
		Delay
		Travel Time Reliability (Variation in travel time)
		Vehicle Miles Traveled
		Vehicle Hours Traveled
		Throughput
	Safety	Crash Rate (Crashes per million VMT)
		Number of Crashes
		Crash Severity (Sever crashes per million VMT)
		Number of Injuries and Fatalities
		Number of Property Damages
	Environment	Vehicle Emissions (Emission of hydrocarbons, carbon monoxide and nitrogen oxides)
Adaptive Traffic Signal Technology	Operation	Travel Time
		Delay
		Intersection Delay
		Travel Time Reliability (Variation in travel time)
		Volume to Capacity Ratio
		Cycle Length
		Green to Cycle Length Ratio
		Percentage of Vehicles Arriving on Green
		Split Failure
		Stops
	Safety	Number of Crashes
		Crash Severity (Number of sever crashes per million VMT)
		Number of Conflict Movements
	Economic	Deployment Costs
		Fuel Consumption
	Environment	Emissions (Emission of greenhouse gases, carbon dioxide, hydrocarbons, nitrogen oxides, and volatile organic compounds)
Bicycle and Pedestrian Management	Operation	Level of Service
		Bicycle and Pedestrian Facility Mileage
		Bike and Pedestrian Volume
	Safety	Number of Bicycle and Pedestrian Involved Crashes
		Number of Fatal Bicycle or Pedestrian Crashes
	Environment	Air Quality (Vehicle travel delay*Gallon of fuel/hour *Passenger car average emission of carbon dioxide + nitrogen oxides + volatile organic compounds)
		Emission of Greenhouse Gases

Continued, **Table 4.1: Performance measures based on operation, safety, economic and environmental aspect of different TSM&O strategies**

TSM&O Strategy	Sub-category	Performance Measure
Corridor and Arterial Traffic Management	Operation	Travel Time
		Speed

		Delay
		Intersection Delay
		Travel Time Reliability (Variation in daily travel time)
		Vehicle Miles Traveled=VMT
		Vehicle Hours Traveled=VHT
		Person Miles Traveled=PMT
		Person Hours Traveled=PHT
		Mobility Index= PMT/VMT
		Average Daily Traffic
		Average Daily Traffic per Freeway Lane
		Bottleneck Ranking
	Safety	Crash Rate (Crashes per million VMT)
		Number of Incidents on System per Yearly VMT
		Number of Incidents/Injuries near Conflict Points per Number of Conflict Points
	Economic	Cost of Delay [Average value of time (dollar/person-hour)*total delay (person-hour)]
		Fuel Cost
	Environment	Emission of Greenhouse Gases
		Emission of Carbon Dioxide
Freeway Management	Operation	Travel time
		Travel time Index
		Buffer Time Index
		Planning Time Index
		Delay
		Delay per Vehicle Mile of Travel
		User Delay Cost
		Percent of Congested Travel
		Vehicle Mile Traveled
		Vehicle Hour Traveled
		Volume to Capacity Ratio
		Level of Service
		Congestion Hours
		Duration of Congestion
		Weighted Congestion Hours
		Congestion Index
		Congested Lane Traveled
		VMT on Congested Roads
		Accident Clearance Time
	Safety	Crash Rate (Number of crashes per million VMT)
		Number of Crashes
		Fatality Crash Rate (Number of fatalities per VMT)
		Number of Fatalities
		Crash Response Time
	Environment	Air Quality Index (On a scale from 0 to 100 depending on the presence of ozone, particulate matter, carbon monoxide, Sulphur dioxide)
		Emissions (Emission rate of nitrous oxides, volatile organic compound, and carbon monoxide)
		Fuel Consumption per VMT

Continued, **Table 4.1: Performance measures based on operation, safety, economic and environmental aspect of different TSM&O strategies**

TSM&O Strategy	Sub-category	Performance Measure
High Occupancy Vehicle (HOV) Lanes	Operation	Travel time
		Speed
		Delay
		Trip Reliability (Percentage of time vehicle travels less than 45 mph)
		Passenger Miles Traveled
		Volume to Capacity Ratio
		Person Throughput
	Safety	Crash Rate (Crashes per 100 million VMT)
		Percentage of Collision Occurred in HOV Lane
	Environment	Air Quality (Vehicle travel delay*Gallon of fuel/hour*Passenger car average emission of carbon monoxide + nitrogen oxides + volatile organic compounds)
		Emissions (Emission of carbon monoxide, nitrogen oxide, and volatile organic compounds)
Pricing/Toll Roads	Operation	Travel time
		Speed
		Delay
		Travel Time Reliability (Variation in travel time)
		Vehicle Throughput
	Safety	Crash Rate (Crashes per 100 million VMT)
		Number of Crashes
		Incident Clearance Time
	Economic	Fuel Efficiency (Vehicle travel distance per gallon of fuel consumed)
		Property Value
		Revenue
	Environment	Emission Rate (Emission rate of nitrogen oxides, carbon monoxide, particulate matter)
Ramp Metering	Operation	Travel time
		Speed
		Queue Length
		Ramp Volume
	Safety	Number of Crashes
	Environment	Fuel Consumption
Geometric Design	Operation	Travel time
		Speed
		Delay
		Volume to Capacity Ratio
		Capacity
		Volume
	Safety	Crash Rate (Crashes per million VMT)
		Number of Crashes
Traffic Signal Program Management	Operation	Travel time
		Delay
		Stops
	Environment	Fuel Consumption
		Emission (Emission of nitrogen oxides and carbon dioxide)

Continued, **Table 4.1: Performance measures based on operation, safety, economic and environmental aspect of different TSM&O strategies**

TSM&O Strategy	Sub-category	Performance Measure
Signal Timing	Operation	Travel Time
		Delay
		Volume to Capacity Ratio
		Cycle Length
		Green Time
		Split Failure/Cycle Failure
		Green Occupancy Ratio
		Red Occupancy Ratio During First Five Seconds of Red
	Safety	Average Number of Vehicle Entering he Intersection During the Yellow Change
		Percentage of Cycle that Experience Red Cycle Violation
		Number of Speeding Related Fatalities
		Number of Motorcyclist Fatalities
		Number of Unhelmeted Motorcyclist Fatalities
	Economic	Value of Travel Time
		Vehicle Operation Cost (Fuel)
		Vehicle Operation Cost (Non-fuel)
Transit Operations	Operation	Delay
		Travel Time Reliability (Percent of bus/rain trips on time)
		Number of Vehicle Trips
		Ridership (Number of trips taken by public transit)
		Number of Transfer
		Access to Transit
	Safety	Number of Crashes (Crashes per VMT, per year, per 1,000 passenger trips)
		Rate of Injuries (Number of injuries per 100 million VMT)
		Rate of Fatalities (Number of fatalities per 100 million VMT)
	Economic	Workers Employed by Freight/Bus Transit Companies
		Percentage of Jobs/Business Served by Bus Transit
		Percentage of Visitors Who Arrive/Depart Resort Destination by Bus Transit
	Environment	Fuel Consumption
		Emission (Emission of greenhouse gases, nitrogen oxide, carbon dioxide)
Transit Signal Priority	Operation	Transit Time Match (Transit vehicles adherence to their schedules)
		Transit Travel Time
		Traffic Queue Length
		Signal Cycle Failures
		Frequency of Transit Signal Priority Calls
		Running Time Mean and Variance
		On-time Performance
		Passenger Wait Times
		Total Travel Time
		Delay at Intersection
		Side Street Queue Length
		Travel Time for the Bus and Car
		Delay to the Bus and Car
		Waiting Time for Outbound Buses
		Side Street Queue Length
	Safety	Percentage of Cycle that Experience Red Cycle Violation
		Crash Frequency
		Pedestrian Fatalities
	Environment	Emission (Emission of total organic gases, carbon monoxide, particulate matter and nitrogen oxides)

Continued, **Table 4.1: Performance measures based on operation, safety, economic and environmental aspect of different TSM&O strategies**

TSM&O Strategy	Sub-category	Performance Measure
Travel Demand Management	Operation	Vehicle Miles Traveled
		Number of Trips
		Count of Biking and Walking
		Number of Single Occupancy Vehicle
		Change in Travel Behavior
		Percent of Commute Transit
	Environment	Emission (Emission of total organic gases, carbon monoxide, particulate matter and nitrogen oxides/ Emission of greenhouse gases)
Freight	Operation	Travel Time
		Speed
		Delay
		Travel Time Index (Ratio of peak period travel time and free-flow travel time)
		Travel Time Reliability (Daily travel time variation)
		Vehicle Miles Traveled
		Volume to Capacity Ratio
		Overnight Truck Parking
		Bottleneck Ranking
	Safety	Crash Rate (Crashes per 100 million VMT)
		Fatality Rate (Fatalities per 100 million VMT)
		Fatal Crash Rate (Fatal crashes per 100 million VMT)
		Highway-rail at Grade Incident
	Economic	Congestion Cost
	Environment	Emission (tons/day of particulate matter, nitrogen oxides, volatile organic compounds, ozone and greenhouse gases)
		Fuel Consumption of Heavy Truck per Mile
Road Weather Management	Operation	Travel Time Reliability (Variation in travel time)
		Regain Time (Time needed for returning to normal traffic operation after a weather emergency)
	Safety	Number of Crashes
		Number of Fatalities
	Economic	Tons of Salt and Chemical Usage

Organizations and Agencies Categorization

There has been substantial growth in the development and use of performance measures in transportation during the last 20 years. At the federal level, transportation agencies participated in testing many planning and measurement efforts. At the state level, transportation agencies are frequently leading agencies in applying performance-based management. At the local level, transit agencies have used performance measures for many years.

Another categorization of performance measures was addressed based on the agencies which conducted and funded related research works, or implemented different performance measures. Table 4.2 summarizes various agencies using performance measures in adoption, implementation or in research level. Performance measures are categorized based on four sub-areas: operation, safety, economic and environment. The studies were reviewed to find out which agencies are conducting or funding research works related to different performance measures. This table will inform the practitioners about which performance measures are frequently used by major organizations. For example, travel time is the most commonly used performance measures to evaluate the operational effectiveness of TSM&O strategies, while crash rate and number of crashes are the most common measures for safety evaluation.

Table 4.2: Performance measures adopted or under research by different agencies

Performance Measures	Organization
Sub-category: Operation	
Travel Time	NCHRP, FHWA, ODOT, VDOT, TxDOT, Nevada DOT, MnDOT, INDOT, University Transportation Center for Alabama, ITS-CT
Travel Time Reliability (Variation in travel time)	NCFRP, FHWA VDOT, ODOT, NYSDOT, CDOT, University Transportation Center for Alabama,
Travel Time Index	NCDOT, ODOT, FDOT, FHWA, Delaware Valley Regional Planning Commission,
Buffer Time Index	FHWA, Delaware Valley Regional Planning Commission,
Planning Time Index	Delaware Valley Regional Planning Commission,
Duration of Vehicle Trips	FHWA, CDOT
Speed	NCHRP, NCFRP, ODOT, VDOT, MDOT, WSDOT, TxDOT, MnDOT, University Transportation Center for Alabama, FHWA
Delay	NCHRP, FHWA, FDOT, ODOT, VDOT, ODOT, MDOT, TxDOT, INDOT
Intersection Delay	California PATH,
Delay per Vehicle Mile of Travel	TxDOT
Vehicle Miles Traveled	NCHRP, TxDOT, WSDOT, ODOT, FDOT, FHWA
Vehicle Hours Traveled	FHWA
Person Miles Traveled	California PATH
Person Hours Traveled	FHWA
Volume to Capacity Ratio	INDOT, ODOT, FDOT, FHWA
Vehicle Throughput	VDOT, ODOT, FHWA
Person Throughput	Maryland, DOT
Queue Length	FDOT, FHWA
Congestion Hours	INDOT
Duration of Congestion	Delaware Valley Regional Planning Commission,
Weighted Congestion Hours	INDOT
Congestion Index	INDOT
VMT on Congested Roads	Transportation Planning Board
Cycle Length	INDOT
Green to Cycle Length Ratio	INDOT
Percentage of Vehicle Arriving on Green	California PATH
Green Time	INDOT
Green Occupancy Ratio	INDOT
Red Occupancy Ratio during First Five Seconds of Red	INDOT
Number of Double Parking	FHWA,
Parking Space Availability (Percentage of spaces occupied)	FHWA
Split Failure	INDOT
Stops	NCHRP
Level of Service	FHWA
Bicycle and Pedestrian Facility Mileage	WSDOT,
Bike and Pedestrian Volume	ODOT, WSDOT, MnDOT
Bottleneck Ranking	WSDOT
User Delay Cost	MDOT
Accident Clearance Time	NCDOT
Trip Reliability (Percentage of time vehicle travels less than 45 mph)	WSDOT
Ramp Volume	WisDOT
Ridership (Number of trips taken by public transit)	ODOT, Chicago Metropolitan Agency for Planning
Number of Transfer	CDOT
Access to Transit	Chicago Metropolitan Agency for Planning (CMAP)
Transit Time Match (Transit vehicles adherence to their schedules)	WSDOT

Continued, **Table 4.2: Performance measures adopted or under research by different agencies**

Performance Measures	Organization
Transit Travel Time	WSDOT
Frequency of Transit Signal Priority Calls	WSDOT
Count of Biking and Walking	ODOT
Number of Single Occupancy Vehicle	ODOT
Percent of Commute Transit	ODOT
Overnight Truck Parking	Maryland, DOT
Regain Time	MDOT
Sub-category: Safety	
Crash Rate	NCHRP, FHWA, ODOT, VDOT, NCDOT, TxDOT, FDOT, DDOT
Number of Crashes	NCHRP, Illinois Center for Transportation, TxDOT, Nevada DOT, MnDOT, CDOT, University Transportation Center for Alabama, FHWA
Crash Severity	ODOT, University Transportation Center for Alabama,
Fatality Rate	NCFRP, TxDOT, ODOT, FDOT, DDOT, NCHRP
Rate of Injuries	VDOT,
Number of Injuries	FDOT, TxDOT,
Number of Fatalities	FDOT, TxDOT, NCHRP, FHWA
Number of Property Damages	FDOT, VDOT
Time-to-Collision	Texas Transportation Institute
Crash Response Time	FHWA, TxDOT
Number of Bicycle and Pedestrian Involved in Crashes	VDOT, WDOT
Number of Fatal Bicycle or Pedestrian Crashes	WDOT
Percentage of Collision Occurred in HOV Lane	California PATH
Average Number of Vehicle Entering Into the Intersection During the Yellow Change	TxDOT,
Percentage of Cycle that Experience Red Cycle Violation	TxDOT
Number of Speeding-related Fatalities	FHWA
Number of Motorcyclist Fatalities	WSDOT, VDOT, FHWA
Number of Unhelmeted Motorcyclist Fatalities	FHWA
Percentage of Cycles that Experience Red Cycle Violations	VDOT, Texas Transportation Institute
Crash Frequency	VDOT
Pedestrian Fatalities	Connecticut DOT
Highway-rail at Grade Incident	NCFRP
Sub-category: Economic	
Business Turnover	VDOT
Commercial Land Values	VDOT
Property Value	NCHRP, FDOT, ODOT,
Deployment Costs	DOT
Fuel Consumption	Nevada DOT, MnDOT, TxDOT, ITS-CT, FHWA
Cost of Delay	ODOT
Fuel Efficiency	---
Revenue	Victoria Transport Policy Institute
Value of Travel Time	Greater London Authority
Workers Employed by Freight rail/bus Transit Companies	CDOT
Percentage of Jobs/Business Served by Bus Transit	CDOT
Percentage of Visitors who Arrive/Depart Resort Destination by Bus Transit	CDOT
Congestion Cost	Maryland, DOT
Tons of Salt and Chemical Usage	FHWA
Fuel Consumption of Heavy Truck per Mile	ODOT

Continued, **Table 4.2: Performance measures adopted or under research by different agencies**

Performance Measures	Organization
Sub-category: Environment	
Emission (hydrocarbons, carbon monoxide, nitrogen oxides and volatile organic compounds)	TxDOT, FDOT, NYSDOT, WSDOT, ODOT, University Transportation Center for Alabama, NCHRP, NCFRP, FHWA, Texas Transportation Institute
Carbon dioxide Emission	TxDOT, FDOT, NYSDOT, WSDOT, ODOT, NCHRP, NCFRP, FHWA
Emission of Greenhouse Gas	WDOT, FDOT, ODOT
Air Quality	FHWA
Air Quality Index	TxDOT

Performance Measures Complementary Information

In this section, additional information is provided to make it easy for practitioners to quickly find major characteristics of various performance measures. Table 4.3 presents the definition, spatial scope, and time scale of each performance measures. In the definition column, performance measures are explained for comprehension and ease of use. To use the performance measure in the evaluation process, the practitioner needs to first understand the definition and units of the measures. Sometimes it is difficult to understand a measure just by its name. For example, travel time reliability basically means how much passengers can rely on their usual experienced travel time. The proper definition of travel time reliability includes measures of dispersion or spread of travel time distribution. Using this definition, it can be understood that travel time reliability can be measured via plotting travel time distribution. The unit of the value used to evaluate system performance is also presented for each performance measures.

Spatial scope demonstrates the influence area of each performance measures. The spatial scope determines the level of detail provided in a performance measure potentially ranging from a point or intersection to a broad, wide region. Practitioners will gain a better understanding of performance measures from their spatial scope about. The time scale of different performance measures is also tabulated. Time scale shows the influence timeframe of each performance measures and duration in which data collection should be conducted. For example, travel time is measured by a.m/p.m peak periods, midday and daily, while the safety performance measures are measured annually. Researches and practitioners need this information to do background study, and evaluate characteristics and importance of a specific performance measure.

Table 4.3: Performance measures with definition, units, spatial scope, and time scale

Performance Measure	Definition	Units	Spatial Scope	Time Scale
Sub-category: Operational				
Travel Time	Average time consumed by vehicles travelling a fixed distance	Minutes	Specific points on a section or a representative trip; separate for GP and HOV lanes	Peak hour, a.m./p.m. peak period, midday, daily
Travel Time Reliability	Measure of dispersion, or spread of travel time distribution	Minutes	Specific section or a representative trip only	Peak hour, a.m./p.m. peak period
Travel Time Index	Ratio of actual travel rate to ideal travel rate	None; Minimum value = 1.00	Section and area wide as a minimum; separately for GP and HOV lanes	As needed
Buffer Time Index	Extra time that travelers must add to their average travel time when planning trips to ensure on-time arrival	Percentage	Section and area wide	Peak hour, a.m./p.m. peak period, midday, daily
Planning Time Index	Total time a traveler should allow to ensure on-time arrival	Percentage	Section and area wide	Peak hour, a.m./p.m. peak period, midday, daily
Speed	Average speed obtained by the vehicles in a fixed distance	Mile per hour	Specific points on a section or a representative trip only; separate for GP and HOV lanes	Peak hour, a.m./p.m. peak period, midday, daily
Delay	Excess travel time used on a trip, facility, or freeway segment beyond what would occur under ideal conditions	Vehicle hours	Section and area wide as a minimum; separate for GP and HOV lanes	Peak hour, a.m./p.m. peak period, midday, daily
Intersection Delay	Excess travel time used on a trip due to the intersection beyond what would occur without the intersection	Vehicle hours	Intersection	Peak hour, a.m./p.m. peak period, midday, daily
Delay per Vehicle Miles Traveled	Excess travel time used on a trip, facility, or freeway segment beyond what would occur under ideal conditions divided by the VMT	Vehicle hours	Section and area wide as a minimum; separate for GP and HOV lanes	Peak hour, a.m./p.m. peak period, midday, daily
Vehicle Miles Traveled	Product of the number of vehicles traveling over a length of freeway, times the length of the freeway	Vehicle per mile	Section and area wide	Peak hour, a.m./p.m. peak period, midday, daily
Vehicle Hours Traveled	Product of the number of vehicles traveling over a length of freeway, times the average travel time.	Vehicle per hour	Section and area wide	Peak hour, a.m./p.m. peak period, midday, daily
Person Miles Traveled	Product of the number of passengers traveling over a length of freeway, times the length of the freeway	Person per mile	Section and area wide	Peak hour, a.m./p.m. peak period, midday, daily

Continued, **Table 4.3: Performance measures with definition, units, spatial scope, and time scale**

Performance Measure	Definition	Units	Spatial Scope	Time Scale
Person Hours Traveled	Product of the number of vehicles traveling over a length of freeway times the average travel time	Person per hour	Section and area wide	Peak hour, a.m./p.m. peak period, midday, daily
Volume to Capacity Ratio	Number of vehicles at a snapshot in time divided by the roadway's capacity	Decimal	Section and area wide	Peak hour, a.m./p.m. peak period, midday, daily
Vehicle Throughput	Number of vehicles travelling a freeway	Vehicle per unit time	Section and area wide	Peak hour, a.m./p.m. peak period, midday, daily
Person Throughput	Number of persons travelling a freeway in vehicles	Person per unit time	Section and area wide	Peak hour, a.m./p.m. peak period, midday, daily
Queue Length	Number of vehicles stopped in a lane behind the stop line at a traffic signal	Number	Intersection	Peak hour, a.m./p.m. peak period, midday, daily
Congestion Hours	Average number of hours during specified time periods in which road section are congested with speeds less than 90 percent of free flow speed	Hours	Section and area wide	Weekdays (6:00 a.m. to 10:00 p.m.)
VMT on Congested Roads	Total vehicle miles traveled on congested road sections with speeds less than 90 percent of free flow speed	Vehicle per hour	Section and area wide	Weekdays (6:00 a.m. to 10:00 p.m.)
Cycle Length	Total signal time to serve the entire signal phases, including the green time plus any change interval.	Seconds	Intersection	Peak hour, a.m./p.m. peak period, midday, daily
Green Time	Total number of seconds per cycle that the green indication is actually displayed to that movement	Seconds	Intersection	Peak hour, a.m./p.m. peak period, midday, daily
Green to Cycle Length Ratio	Total number of seconds per cycle that the green indication is actually displayed to that movement, divided by the total signal time	No unit	Intersection	Peak hour, a.m./p.m. peak period, midday, daily
Percentage of Vehicle Arriving on Green	Proportion of vehicles that arrive to a green light versus the proportion that arrive to a red light	Percentage	Intersection	Peak hour, a.m./p.m. peak period, midday, daily
Green Occupancy Ratio	Number of seconds a green time is occupied by the vehicles crossing the intersection divided by the total green time	No unit	Intersection	Peak hour, a.m./p.m. peak period, midday, daily
Red Occupancy Ratio during first seconds of Red	Number of seconds during the first 5 seconds vehicle is approaching the intersection, divided by 5.	No unit	Intersection	Peak hour, a.m./p.m. peak period, midday, daily
Number of Double Parking	Number of vehicles standing or parking on the roadway side of a vehicle already stopped, standing or parked at the curb.	Count	Section and area wide	Peak hour, a.m./p.m. peak period, midday, daily

Continued, **Table 4.3: Performance measures with definition, units, spatial scope, and time scale**

Performance Measure	Definition	Units	Spatial Scope	Time Scale
Stops	Number of vehicles stopped at the intersection due to the traffic signals	Vehicle count	Intersection	Peak hour, a.m./p.m. peak period, midday, daily
Bicycle and Pedestrian Facility Mileage	Total linear miles of designated bike lane and sidewalk	Miles	Section and area wide	No time scale
Bike and Pedestrian Volume	Number of bikes and pedestrians on a specific road segment	Bikes per hour/ Pedestrians per hour	Section and area wide	Peak hour, a.m./p.m. peak period, midday, daily
Bottleneck Ranking	Ranked condition of an existing bottleneck with three parameters: travel speed, percentage of travel speed below 35 mph, and travel reliability	N/A	Specified Segment	Peak hour, a.m./p.m. peak period, midday, daily
Accident Clearance Time	Time between the first recordable awareness of the accident (detection/notification/verification) by a responsible agency and first confirmation that all lanes are available for traffic flow	Hours	Location of the accident	Accident time frame
Ramp Volume	Volume of traffic per hour on a specific ramp	Vehicle per hour	Ramp	Peak hour, a.m./p.m. peak period, midday, daily
Ridership	Number of trips taken by public transit	Passenger count per day	Area wide	Daily
Transit Time Match	Absolute difference between actual transit arrival time and scheduled arrival time at each timing point	Minutes	Each timing point on the route	Daily
Frequency of Transit Signal Priority Calls	Number of calls per hour the system requests signal priority.	Calls per hour	Intersection	Peak hour, a.m./p.m. peak period, midday, daily
Count of Biking and Walking	Number of non-motorized trips (biking and walking) in a specific area	Bicycle and pedestrian count	Area wide	Peak hour, a.m./p.m. peak period, midday, daily
Number of Single Occupancy Vehicle	Number of vehicles with only one passenger on a specific segment of a road	Vehicle per hour	Segment and area wide	Peak hour, a.m./p.m. peak period, midday, daily
Regain Time	Time needed for any transportation system to return to normal seasonal condition after a weather emergency.	Hours	Segment and/or area wide	Seasons

Continued, **Table 4.3: Performance measures with definition, units, spatial scope, and time scale**

Performance Measure	Definition	Units	Spatial Scope	Time Scale
Sub-category: Safety				
Crash Rate	Total crashes divided by freeway VMT for the time period considered	Number per 100 million vehicle miles	Section wide, Area wide	All safety measures computed annually
Number of Crashes	Crashes as defined by the state; i.e. number for which a police accident report form is generated	Number	Intersection, Section wide, Area wide	
Fatality Rate	Total fatal crashes (those for which a police accident report form is generated, where at least one fatality occurred) divided by freeway VMT for the time period considered	Number per 100 million vehicle miles	Section wide, Area wide	
Number of Fatalities	Total fatal crashes (those for which a police accident report form is generated, and at least one fatality occurred)	Count	Intersection, Section wide, Area wide	
Number of Property Damages	Number of property damages only (PDO)	Count	Area wide	
Time to Collision	Time takes for a vehicle to collide into another if they continue at the same speed without trying to avoid each other	Minutes	Intersection, Section wide, Area wide	
Number of Bicycles and Pedestrians Involved in Crashes	Number of bicycles and pedestrians involved in crashes as defined by the state; i.e. number for which a police accident report form is generated	Count	Intersection, Section wide, Area wide	
Number of Fatal Bicycle or Pedestrian Crashes	Number of crash fatalities involving bicycles or pedestrians for which a police accident report form is generated, and at least one fatality occurred.	Count	Intersection, Section wide, Area wide	
Percentage of Collisions Occurring in HOV Lane	Number of collisions occurring in HOV lanes divided by the total collision on a specific segment of the road.	Percentage	Section wide	
Pedestrian Fatalities	Number crashes involving pedestrian fatalities for which a police report form is generated, and at least one fatality occurred	Count	Intersection, Section wide, Area wide	
Highway-rail at Grade Incident	Incidents occurring at highway-rail crossing for which police report for is generated	Count	Highway-rail crossing, Area wide	
Sub-category: Economic				
Business Turnover	Numeric value representing total sales normally over a year's period	Dollars	Area wide	Yearly
Commercial Land Values	Overall value of a piece of property	Dollars	Area wide	Yearly
Deployment Costs	Cost of any new technology deployed in the road	Dollars	Area wide	As needed
Fuel Consumption	Amount of fuel a vehicle uses to travel a particular distance at a particular speed.	Gallons	Section or area wide	Yearly
Cost of Delay	Total delay multiplied by average value of time	Dollars	Section or area wide	Yearly
Fuel Efficiency	Vehicle travel distance per gallon of fuel consumed	Miles per gallon	Area wide	Yearly
Workers Employed by Freight/bus Transit Companies	Number of workers employed by freight/bus transit companies within a specific time period	Count	Based on the area transit company coverage	Yearly

Continued, **Table 4.3: Performance measures with definition, units, spatial scope, and time scale**

Performance Measure	Definition	Units	Spatial Scope	Time Scale
Percentage of Visitors who Arrive/Depart Resort Destination by Bus Transit	Percentage of visitors using public transport to arrive or depart recreational destination	Percentage	Area wide	Yearly
Congestion Cost	Cost associated with the congestion including delay cost, wasted fuel cost, emission cost, etc.	Dollar	Section or area wide	Yearly
Tons of Salt and Chemical Usage	Tons of salt and chemical used as deicer during the winter	Tons	Area wide	Yearly
Fuel Consumption of Heavy Truck per Mile	Amount of fuel consumed by heavy truck per mile of travel	Gallons per mile	Section and area wide	Yearly
Sub-category: Environment				
Emissions (hydrocarbons, carbon monoxide, nitrogen oxides, volatile organic gases, carbon dioxide and greenhouse gases)	Modeled hazardous gases attributable to roads and highways divided by VMT	Tons	All environmental measures computed area wide; section level may be computed if multiple years are used	All environmental measures computed annually
Air Quality	Vehicle travel delay multiplied by gallons of fuel per hour multiplied by passenger car average emission	Tons		
Air Quality Index	Score the air quality depending on the presence of O_3, PM, CO, SO_2	0 to 100		
Fuel Consumption per VMT	Fuel consumed by vehicles divided by the average VMT on a specific area.	Gallons per vehicle miles		

Performance Measures: Quantifying Techniques, and Challenges

This part of the report contains the popular methods of calculating different performance measures, types of equipment used, opportunities, and challenges to evaluate those performance measures.

Operational Performance Measures:

Operational performance measures, which are used to evaluate operational effectiveness of different TSM&O strategies, are categorized in Table 4.4 based on the basic required data to quantify performance measures. The first group of PMs requires travel time as the basic data to be calculated. For example, travel time, travel time reliability, travel time index, and buffer time index all require actual travel time as basic data. Then, different studies were reviewed to find out which various techniques and instruments are commonly used to calculate actual travel time. Different agencies and organizations have implemented or are implementing different technologies to collect data for travel time. Next, advantages and disadvantages of those techniques are summarized in the table, which will give the practitioners a clear idea about the characteristics of each method.

Test vehicle technique is the oldest method to calculate the travel time which has been used since the late 1920s. Traditionally, this method involves a data collection vehicle within which an observer records travel time at predefined checkpoints along a travel route. There are three levels of instrumentation used to measure travel time with a test vehicle: manual, distance measuring instrument (DMI), and global positioning system (GPS). Another method is license plate matching, which consists of collecting license plate numbers and arrival times at various checkpoints, matching the license plates between consecutive checkpoints, and computing travel times from the difference in arrival times. The basic methods of collecting and processing license plates are manual, portable computer, video with manual transcription and video with character recognition. The probe vehicle techniques are typically intelligent transportation system (ITS) applications designed for collecting data in real time. ITS probe vehicle can use automatic vehicle identification (AVI), ground based radio navigation, cellular geo-location, GPS or Bluetooth devices.

The second set of operational performance measures can be quantified using traffic count, speed, and amount of travel. Traffic count and speed data are collected from loop detector, road tubes, infrared, microwave, acoustic, ultrasonic, video image processor, and etc. Traffic volume and speed counting methods are summarized in this section. There are two basic techniques: intrusive (installed within or across the pavement on roads and bridges) and non-intrusive (installed above or on the sides of the roads and bridges with minimum disruption to traffic flow). Intrusive detector technologies include magnetic detectors, inductive loop, pneumatic road tube, and weigh-in-motion. Non-intrusive techniques include infrared, microwave, passive acoustic, ultrasonic, video image processing, and Bluetooth wireless signals. Advantages and disadvantages of each technology are reviewed and summarized in Table 4.4.

Pedestrian and bicycle counts are the next set of performance measure categorized in this table with their data capturing techniques. Performance measures related to parking (i.e. number of double parking, parking space availability) are commonly evaluated either by field survey or geographic information system (GIS). Field surveys are associated with high costs but accurate results while GIS gives cheaper and faster solutions with more potentially questionable results. Measures related to public transit ridership are traditionally conducted by household survey or smart card technology.

Table 4.4: Operational performance measures, data collection techniques, advantages and disadvantages

Performance Measures	Techniques to Collect Data	Instrumentation Level	Advantages	Disadvantages
• Travel Time • Travel Time Reliability (Variation in travel time) • Travel Time Index • Buffer Time Index • Planning Time Index • Speed • Delay • Intersection Delay • Congestion Hours	Test vehicle technique	Manual	• Low initial cost • No special equipment needed • Low required skill level	• High operating cost (high labor requirements) • Greater potential for human error • Limited travel time/delay information available • Limited sample of motorists
		GPS	• Moderate initial cost • Reduction in human error • Data easily integrated into GIS • Detailed speed/delay data available • No vehicle calibration is necessary as with the DMI method	• Reception problems in urban "canyons", trees • Limited sample of motorists • Due to rapidly changing area, difficult to stay updated on what equipment to purchase
		Electronic DMI	• Moderate initial cost • Proven technology • Reduction in human error • Very detailed speed/delay data available • Commercially available software provides a variety of collection and analysis features	• Not readily adaptable to a geographic information system • Limited sample of motorists
	License plate matching	Manual	• Low initial cost • Minimum amount of simple field equipment required	• High operating cost • Accuracy may be questionable • Data reduction is time-consuming
		Portable Computer	• Low operating cost • Travel times from large sample of motorists • Continuum of travel times during data collection	• Accuracy problems with data collection, spurious matches • Limited geographic coverage on single day • Required highly motivated and moderately skilled observers because of fatigue
		Video with Manual Transcription	• Travel times from large sample of motorists • Continuum of travel times during data collection	• Data reduction is time consuming • Limited geographic coverage on single day
		Video with Character Recognition	• Low operating cost • Travel times from large sample of motorists • Continuum of travel times during data collection	• High initial costs (if equipment purchased) • Limited geographic coverage on single day • Accuracy is sensitive to ambient condition • Technologically intensive and typically requires outsourcing

Continued, **Table 4.4: Operational performance measures, data collection techniques, advantages and disadvantages**

Performance Measures	Techniques to Collect Data	Instrumentation Level	Advantages	Disadvantages
	ITS probe vehicle	Signpost-based	• Low operating cost • Some systems can collect passenger counts • Some systems can collect fuel consumption, oil pressure or cooling temperature	• Need routine calibration to prevent erroneous data collection • Typically used for transit vehicles (includes loading and unloading times) • Limited coverage area
		AVI (Automated vehicle identification)	• Low operating cost • Very accurate data collection • Continuous data collection • Can collect data from particular lanes	• Very high initial cost for AVI infrastructure • Limited to instrumented location • Data collection limited to the number of tags in use within the area • Privacy issues
		Ground-based Radio Navigation	• Low initial cost • Available consumer product	• Low data accuracy • Typically used for transit vehicles • Sample dependent on equipped vehicles • Less sophisticated than GPS technologies
		GPS	• Increasingly available consumer product • Low operating cost	• Sample dependent on equipped vehicles • Privacy issues
		Cellular Phone Tracking	• Widely available consumer product • No in-vehicle equipment to install • Large potential sample	• Accuracy questionable for detailed applications • Privacy issues
		Bluetooth Wireless Signal	• Widely available consumer product • Low operating cost • Large potential sample • Continuous data collection • No in vehicle equipment to install	• Privacy issues • Relies on driver's Bluetooth-enabled device usage

Continued, **Table 4.4: Operational performance measures, data collection techniques, advantages and disadvantages**

Performance Measures	Techniques to Collect Data	Instrumentation Level	Advantages	Disadvantages
• Annual Daily Traffic (ADT) • Vehicle Miles Traveled (VMT) • Vehicle Hours Traveled (VHT) • Person Miles Traveled (PMT) • Person Hours Traveled (PHT) • Volume to Capacity Ratio (V/C) • Person Throughput • Stops • Speed • Intersection Delay • Queue Length • VMT on Congested Roads • Percent of vehicle arriving on green • Ramp volume • Level of Service • Number of Single Occupancy Vehicle • Regain Time	Non-intrusive techniques	Infrared (Active, Passive)	• Low operating cost • Accurate measurement of vehicle position, speed, and vehicle class • Multiple lane coverage	• Active detector may be affected by snow • Sensitivity to vehicles reduces in rain and for passive detector
		Microwave (Doppler, Radar, and Passive Millimeter)	• Low operating cost • Flexible installation position • Generally insensitive to inclement weather • Single detector sufficient to measure speed • Multiple lane coverage	• Restriction of antenna beam bandwidth • Doppler sensors cannot detect stopped vehicles
		Passive Acoustic	• Low operating cost • Multiple lane coverage	• Cold temperature affects accuracy • Some models have poor performance in slow traffic
		Ultrasonic (Pulse and Doppler)	• Low initial cost • Multiple lane coverage	• Temperature and air can affect performance • Problems on moderate to high speed
		Video Image Processor	• Low maintenance cost • Multiple lane coverage • Rich data types • Multi-media data	• Affected by inclement weather, shadows, vehicle projection, and time of day
		Bluetooth Wireless Signal	• Widely available consumer product • Low operating cost • Large potential sample	• Cannot directly give volume data • Privacy issues
	Intrusive techniques	Magnetic (Passive) Detectors	• Accurate and reliable data • Moderate initial cost	• Extensive effort for installation • Some models need pavement cutting • Disturbs traffic • Cannot detect stopped vehicles
		Inductive Loop (Active Magnetic)	• Mature and well-developed • Well-known to engineers • Low initial cost • Basic traffic data • Accurate and reliable	• High maintenance cost, especially at intersection • Installation deteriorates pavement • Poor performance under bad pavement condition • Disturbs traffic • Installation personnel safety issues • Requires multiple detectors for a location
		Pneumatic Road Tube	• Low initial cost • Gives axle-based classification	• Not durable • Not suitable for high-flow and high-speed roads • Cannot detect two-wheelers
		Weight-in-Motion (WIM)	• Low initial cost • Accurate vehicle classification	• High initial costs • High equipment and maintenance costs • Fixed location • Installation deteriorates pavement

Continued, **Table 4.4: Operational performance measures, data collection techniques, advantages and disadvantages**

Performance Measures	Techniques to Collect Data	Instrumentation Level	Advantages	Disadvantages
• Bike and Pedestrian Volume	Manual Counting	Paper sheets, Traffic Count Boards, Clicker Counters, Smartphone Apps	• Low initial costs • Flexibility to gather additional data about travelers (i.e, directional information, gender, and behaviors) • Applicable to all site types and users • Extremely mobile	• Short-term counts only • Higher operating cost at higher volume locations • Accuracy is subject to data collector fatigue and possible count biases
		Manual Counting with Video Camera	• Flexibility to gather additional data about users (i.e., directional information, gender, and behaviors) • Applicable to all site types and users • Flexibility to slow down or speed up video data during reduction based on volume of users • Data collectors do not have to spend hours in the field—a constraint during poor weather conditions or nighttime data collection • Video can be reviewed at times other than when data are collected to accommodate busy schedules • A single data collector can reduce data for the same time period at multiple sites after video cameras are set up	• Short-term counts only, due to labor costs involved with reducing data • Frequent field visits are necessary to set up cameras, replace batteries and memory cards, and take down equipment • Video cameras are susceptible to theft unless well-obscured and placed out of convenient reach • Problems can arise with video footage (e.g., corrupt files or poor vantage points), requiring the video to be retaken • Requires a fixed pole at the location or a portable pole for mounting the camera
	Automatic Counting	Video Camera with Image Processing	• Minimal human time required to collect counts • Can provide intersection turning movement and crosswalk counts • Portable and straightforward to install where camera mounting locations are available • Video can be used for additional purposes (e.g., facility evaluation and user behavior studies)	• Short-term counts only • Not currently possible to process video in-house (requires a vendor to do the processing)
		Pneumatic Tubes ***(for bicycle counts only)***	• Portable • Easy to set up • Can capture speed and directionality of bicyclists when two tubes are used • Most jurisdictions are familiar with the technology, because they already use it for counting automobiles.	• Susceptible to theft, vandalism, dislodgement, and wear and tear, requiring routine maintenance • May require permission from local jurisdiction for installation, which sometimes requires not using nails • Not usable during times when street sweeping or snowplowing occurs, because the tubes can be dislodged or destroyed

Continued, **Table 4.4: Operational performance measures, data collection techniques, advantages and disadvantages**

Performance Measures	**Techniques to Collect Data**	**Instrumentation Level**	**Advantages**	**Disadvantages**
		Inductive Loop Detectors	• Most jurisdictions are familiar with embedded loop technology, because it is also used to detect vehicles at traffic signals • Can be used for on-street bicycle facilities • Can be battery powered • Long-lasting equipment	• Embedded loops require pavement saw cuts and a minimum pavement thickness • Electromagnetic interference can cause errors • May not detect side-by-side bicyclists • May experience inaccuracies with nonstandard bicycles (e.g., bicycles with trailers or cargo boxes, tandem bicycles) • If it is not possible to cover the entire facility width with the loops, bypass errors will occur when bicyclists ride outside the area covered by the loops
		Passive Infrared	• Small, portable, and easy to install • Battery powered • May be used in combination with another technology to differentiate between bicyclists and pedestrians	• Cannot be used to count bicyclists in mixed traffic • Errors may arise because of occlusion with groups of pedestrians • Device performance can be affected by extreme temperatures
		Active Infrared	• Movable and easy to install • Battery powered • May be used in combination with another technology to differentiate between bicyclists and pedestrians • Very precise error function is highly linear, so applying a multiplicative factor yields very accurate results	• Cannot be used for on-street monitoring • Can count false positives from other objects (e.g. vehicles, insects, leaves, animals, and rain drops) • Errors may arise due to occlusion with groups of pedestrians or side-by-side bicyclists • Requires mounting devices to fixed objects on each side of the trail or sidewalk
		Radio Beams	• Movable and easy to install • Can be hidden in post to discourage tampering or theft • Battery powered	• May experience inaccuracies with groups of pedestrians • Requires mounting devices to fixed objects on each side of the trail within limited distances
		Pressure and Acoustic Pads	• Battery powered • In-ground installation resists vandalism and theft	• Requires users to pass directly above the sensor • Most commonly used on unpaved trails • Acoustic pads can only count pedestrians
		Magnetometer ***(only for bicycle counts)***	• Battery powered • In-ground installation resists vandalism and theft	• Relatively small detection area • Limited application
		Fiber Optic Pressure Sensors	• Can classify users/vehicles based on their weight • Discrete and not susceptible to tampering when embedded in pavement	• Specialized installation process • Potential sources of error have not been rigorously tested

Continued, **Table 4.4: Operational performance measures, data collection techniques, advantages and disadvantages**

Performance Measures	Techniques to Collect Data	Instrumentation Level	Advantages	Disadvantages
• Number of Double Parking • Parking Space Availability (Percentage of spaces occupied)	Field Survey	Roadside Manual Surveys	• Very accurate • Provides detailed information	• High cost • Time consuming • Dependent on weather • Due to large number of signs, manual data collection is difficult
	Geographic Information System	Geographic Information System	• Faster and cheaper • Does not depend on weather • Allows a better overview with zooming tools	• Possible obstruction by upper-layer objects • Distance-measuring tool integrated in software is not very accurate
• Ridership (Number of trips taken by public transit) • Percent of Commute Transit	Survey	Observational Surveys, Household Self-Completion Surveys, Telephone Surveys, Intercept Surveys, Personal Interviews, etc.	• Low cost • Detailed trip information can be obtained • Does not need new technology • Data are highly representative	• Time-consuming • Data accuracy depends on interviewee • Possible inappropriateness of the questions
	Smart Card Technology	Smart Card	• Survey process is minimized • Trip data combined with personal data improves data quality • Examining travel behaviors by reconstructing user trips is easier than doing so by studying existing data	• No information on trip purpose or on user assessment of service can be provided • High implementation cost • Market penetration needs to be sufficient to provide a representative sample of the entire population

Safety Performance Measures:

The National Highway Traffic Safety Administration provides the underpinning traffic safety data for informed highway safety decision-making at the federal, state, and local levels. Accurate, accessible, timely, and standardized data allow decision makers to identify the primary factors related to the sources of crashes and their outcomes, develop and evaluate effective safety countermeasures, support traffic safety operations, measure progress in reducing crashes and their severity, design effective vehicle safety regulations, and target safety funding. The primary data systems of NHTSA are Fatality Analysis Reporting System (FARS), National Automotive Sampling System General Estimates System (NASS GES), National Automotive Sampling System Crashworthiness Data System (NASS CDS), State Data System (SDS), and Crash Outcome Data Evaluation System (CODES). Table 4.5 summarizes the data sources for those data systems and the challenges confront to collect those data. For example, data can be sourced from FARS censuses on police-reported motor vehicle fatalities, as well as other sources such as hospital data, crash data from driver licenses, and vehicle registrations. There is a lack of consistency on accident data collection from police accident reports (PARs). Pedestrian and cyclist accident data are not included, and minor crashes may not be reported. This table provides the practitioners and researchers with various data collection methods in different database systems.

Table 4.5: Safety performance measures, data sources, data collection challenges

Performance Measures	Data Sources	Crash Data Programs Using the Sources	Challenges/Limitations
• Crash Rate • Number of Crashes • Crash Severity • Fatality Rate • Number of Fatalities • Rate of Injuries • Number of Injuries • Number of Property Damages • Number of Fatal Bicycle or Pedestrian Crashes • Number of Speeding-related Fatalities • Number of Motorcyclist Fatalities • Number of Unhelmeted Motorcyclist Fatalities • Pedestrian Fatalities • Highway Rail at Grade Incident	Police Accident Reports (PARs)	FARS, NASS GES, SDS, NAS CDS, CODES	• Lack of consistency in data collection techniques, and data inclusion/exclusion • Data are sometimes missing regarding pedestrians and cyclists • Data available on state level and not at federal level • Exclusion of non-public road collisions • Underreporting of injuries
	Hospital Data	FARS, NASS CDS, CODES	• Lack of consistency between police and hospital data • Poor information on crash circumstances • Data are available on a regional/local basis
	Emergency Hospitals	FARS, NASS CDS, CODES	• Lack of consistency in data collection techniques, and data inclusion/exclusion • Many data on paper • Injured person at crash can go to hospital several days after crash
	Driver Licensing	FARS, CODES	
	Vehicle Registration	FARS, CODES	
	Insurance Data	FARS, NASS CDS, CODES	• Only collisions resulting in an insurance claim will be recorded • Data are affected by the propensity of people to make a claim following a collision • Little experience nationwide to use these data as sources • Practical and commercial difficulties in obtaining and collecting data • Inconsistent data collection method by different companies
	Field Investigation	NASS CDS	
	Techniques	**Instrumentation Level**	**Challenges/Limitations**
• Average Number of Vehicle Entering Into the Intersection During the Yellow Change • Percentage of Cycles Experiencing Red Cycle Violation	Red Light Camera	Red Light Camera	• Rear-end crashes increase due to red light camera implementation

Economic Performance Measures:

Performance measures regarding the economic evaluation of transportation strategies are categorized based on their data collection methods. The opportunities and challenges of various data collection methods are summarized in Table 4.6. This table will give the practitioner a summary of how different performance measures are quantified and their challenges. Business turnover, commercial land values, and property values can be collected from different published economic directories such as Flow of Funds (FOF) accounts published by Federal Reserve Boards. Another reliable method to collect data regarding the financial influence of a particular transportation strategy is conducting interviews.

Another important performance measure to evaluate the economic conditions of an area due to implementation of a transport technique is cost of delay, which is considered a separate category. The required data to quantify this measure are total delay, which can be found from the travel time study and average value of time (VOT). Determining the average value of time is a complex method, as it depends on many variables such as characteristics of the trip, the trip's purpose, the amount of time saved per trip, who is paying for the travel, and the possibility of engaging other productive or enjoyable activities while traveling.

Fuel consumption and fuel efficiency are measured mainly by the National Household Travel Survey (NHTS). Energy Information Administration (EIA) uses this survey information to calculate the number of vehicles per household, the number of gallons of fuel consumed, the types of fuel used, etc. Information about the employees working in a public transit company can be easily collected by the Public Transportation Fact Books published annually.

Tons of salt and chemicals, which are used as a deicing material in the winter, are another important performance measures to evaluate economic effectiveness of transportation strategies. State DOTs purchase history is a good source of data collection for tons of deicing materials used per year. For example, the Minnesota DOT purchases salt through a state bidding program managed by the Materials Management Division (MMD).

Table 4.6: Economic performance measures, data collection processes and challenges

Performance Measures	Data Collection Opportunities and Challenges
• Business Turnover • Commercial Land Values • Property Value	The analysis of business turnover, commercial land value, and property value due to a transportation strategic plan is normally conducted using published economic directories for a specific time period. For example, the value of residential and commercial land can be derived from the Flow of Funds (FOF) accounts published by Federal Reserve Board. Interviews with business owners, managers, and residents also give a substantial amount of data to quantify these performance measures. But due to lack of research, the long-term impact of transportation strategy implementation on commercial development and land remains a controversial issue.
• Cost of Delay	Cost of delay is measured by multiplying total delay in person hours with the average value of time (VOT). One criticism of the commonly used methods of measuring VOT is the reporting average values for entire populations or very large subgroups of travelers. According to recent studies from the National Academies' Transportation Research Board Committee on Transportation Economics, while the use of average values of VOT is straightforward and relatively simple, it assumes a normal distribution when the true distribution is likely skewed. Individual VOT can also vary considerably for the same individual, depending on trip characteristics such as trip time, trip purpose, amount of time saved per trip, who is paying (the traveler or the employed), and the possibility of engaging in other productive or enjoyable activities while traveling.
• Fuel Consumption • Fuel Efficiency • Fuel Consumption of Heavy Truck per Mile	To evaluate these performance measures, the most important data required is fuel consumed by private and commercial vehicles. The National Household Travel Survey (NHTS) is the nation's inventory of local and long-distance travel. NHTS conducts interviews and collect data from the civilian, non-institutionalized population of the United States. The Energy Information Administration (EIA) uses those data sources to calculate number of vehicle per household, gallon of fuel consumed, types of fuel used, price paid for fuel, and fuel economy.
• Workers Employed by Freight rail/bus Transit Companies • Percentage of Visitors who Arrive/Depart Resort Destination by Public Transit	Public transit employees include workers in the functions of vehicle operations, vehicle maintenance, non-vehicle maintenance, and general administration. Employee data can be obtained from published fact books. Public Transportation Fact Book is a very good source to collect data about employees by mode of transit and type of operators.
• Tons of Salt and Chemical Use	Salt and other chemicals have been widely used for ice and snow control on roads in the US, Canada, and other parts of the world. The main product used in North America for deicing is sodium chloride, a readily available and inexpensive product that provides adequate treatment to roadways under winter conditions. To obtain the total amount of road salt and other chemicals used within a specific geographical region, information is gathered from the agencies that use road deicing materials. State DOT purchase history is a good source of data collection for tons of deicing materials used per year. For example, the Minnesota DOT purchases salt through a state bidding program managed by the Materials Management Division (MMD). Other agencies, including counties and municipalities, take advantage of state program. Since the bid amounts represent the estimated usage by each agency, these amounts were starting points for determining the total salt and chemical use. Agencies that use the program are contacted to retrieve the actual amounts of salt applied.

Environmental Performance Measures:

Environmental performance measures of transportation systems are mainly related to emission. There are various ways to calculate the hydrocarbons (HC), carbon dioxides (CO_2), nitrogen oxides (NOx), and particulate matters emissions. One type of emission testing is conducted using a dynamometer and analyzer in a testing lab, allowing an operator to take the vehicle through a prescribed drive cycle. From the data found in the laboratory condition, real-world emissions can be calculated using travel time, speed, and congestion data. Another method is real-world measure, which includes remote sensing or an on-board emission measurement device. Remote sensing measures emission by shooting a light beam through a vehicle's exhaust stream as the vehicle passes the testing equipment. Portable emission measurement systems (PEMS) are small units that can be attached to or set inside a vehicle to collect real world driving data using a probe that is inserted into the tailpipe. Both these methods have their limitations. For example, remote sensing and PEMS cannot measure particulate matters, while dynamometer does not measure real world driving conditions. Table 4.7 gives a summary of popular techniques to quantify vehicle emission and their characteristics.

Table 4.7: Environmental performance measures, testing techniques and their characteristics

Performance Measures	Testing Type	Instrumentation Level	Characteristics of Testing Type
• Emission (hydrocarbons, carbon monoxide, nitrogen oxides, and volatile organic compounds) • Carbon Dioxide Emission • Emission of Greenhouse Gases • Air Quality Index	Certification Testing (Acceptable for Emission Certification)	Chassis Dynamometer and Analyzer	• Normally used for light-duty vehicles • Measures HC, CO, NOx, and PM • Produces consistent and repeatable results • Cannot measure in real-world driving condition
		Engine Dynamometer and Analyzer	• Normally used for heavy-duty vehicles • Measures HC, CO, NOx, and PM • Produces consistent and repeatable results • Cannot measure in real-world driving condition
	Non-certification Testing (Not Acceptable for Emission Certification)	Remote Sensing	• Measures HC, CO, and NOx • Can measure in real-world driving condition • Cannot measure PM • Results cannot be repeated • Limited to one lane where cars pass one at a time
		Portable Emission Measurement	• Measures HC, CO, and NOx • Can measure in real-world driving condition • Cannot measure PM • Results cannot be repeated • Very costly to use on a fleet basis

4.2 Impact of MAP-21 Legislation on TSM&O-specific Performance Measures

This section of the report focuses on the performance measures of MAP-21, and describes the key challenges faced by DOTs while adopting these measures. MAP-21 is a funding and authorization bill to govern United States federal surface transportation spending. Table 4.8 summarizes goals, associated performance measures, and basic characteristics (definition and unit). MAP-21 has six primary goals, which include enhancing safety, improving infrastructure condition, reduction of congestion, increasing system reliability, development of freight movement and economic vitality, and improving environmental sustainability. Each of these goals has some associated performance measures. For example, delay and the percentage of severely congested miles are two basic measures which measure congestion of any area or specific section of a highway.

This report proposes a framework that systematizes performance measurements (from the literature search) in a consistent and accessible way. This proposed systematization has to align with the rules recently published by the Federal Highway Administration (FHWA), under MAP-21 legislation. Table 4.9 shows some of the key aspects that need to be carefully considered within the proposed framework and further aligned with the FHWA published rules. Table 4.9 further provides suggestions to practitioners in dealing with these aspects of TSM&O. As it can be seen from Table 4.9, most of these aspects are, up to some extent, related to the recent developments in sensor technology and the advancements in traffic information recording, which incorporate the use of high temporal and spatial resolutions. For instance, significant attention (in Table 4.9) has been dedicated to probe vehicles, sampling intervals and imputations of missing data, since all these components are closely related to sensor technology.

Table 4.8: MAP-21 goals, performance measures, and primary characteristics (definition and unit)

Goals	Performance Measures	Definition	Units
Safety	Serious injuries per VMT	Total crashes divided by the total vehicle miles traveled, for which a police accident report form is generated, where at least one injury occurred.	Persons per mile
	Fatalities per VMT	Total fatal crashes divided by the total vehicle miles travelled, for which a police accident report form is generated, where at least one fatality occurred.	Persons per mile
	Number of serious injuries	Total crashes for which a police accident report form is generated, where at least one injury occurred.	Persons
	Number of fatalities	Total fatal crashes for which a police accident report form is generated, where at least one fatality occurred.	Persons
	Number of transit-related fatalities	Total fatal crashes related to transit system for which a police accident report form is generated, where at least one fatality occurred.	Persons
Infrastructure Conditions	IRI (International roughness index)	Ride Quality Parameter (IRI) IRI is the International Roughness Index and measures pavement smoothness.	m/km or mm/m (from 0 to 170)
	Pavement structural health index	Percentage of pavement which meet minimum criteria for pavement faulting, rutting and cracking.	Percentage
Congestion Reduction	Delay (thousands of hours)	Time difference between actual travel time and free-flow travel time.	Hours
	Percentage of severely congested miles	Percentage of miles of roadway associated with severe congestion defined by state DOTs.	Percentage
System Reliability	VMT	Miles traveled by vehicles within a specified region for a specified time period (monthly/yearly).	Vehicle per mile
	Travel time reliability	Dispersion (or spread) of the travel time distribution. 95th percentile travel times	Minutes
	Annual Hours of Delay (AHD)	Travel time above a congestion threshold (defined by State DOTs and MPOs) in units of vehicle hours of delay	Hours
	Reliability Index (RI_{80})	Ratio of the 80th percentile travel time to the agency-determined threshold travel time.	None
Freight Movement & Economic Vitality	Combined truck miles travelled (in millions)	Number of millions of miles traveled by trucks within a specified time period (monthly/yearly)	Truck per mile
	Annual hours of truck delay	Travel time above a congestion threshold (defined by State DOTs and MPOs) in units of truck hours of delay	Hours
	Truck Reliability Index (RI_{80})	Ratio of the 80th percentile travel time to the agency-determined threshold travel time.	None
Environmental Sustainability	On-road mobile source emission	Yearly tons of on-road, mobile source criteria air pollutants (VOC, NOx, PM, CO)	Tons per year

Table 4.9: The key TSM&O aspects / components that require careful consideration and further alignment with the federal rulemaking under MAP-21 legislation.

Component	Requirements	Challenges	Suggestions
• Data Collection	• Consistent temporal and spatial data collection • High reliability and accuracy of recorded and imputed data • Efficient missing data imputation approaches	• Time intervals with no probe vehicles • Segments are constantly changing • Segment conflation (remapping) is costly • Low percentage of missing/imputed data • Reliable imputation techniques/approaches	• Procure data at every epoch (time interval) regardless of the existence of probe vehicles • Procure data at the highest available resolution • Avoid sampling rates of exactly 2 minutes • Supply imputed/smoothed data • Denote the confidence of the imputed data • Data provider should strictly adhere to the published standard • Do not use speed limits to fill the missing values • Instead, use smoothed / imputed dataset directly from the probe data provider (HERE,INRIX).
• Measurements	• Consistent throughout observed time (AM and PM peaks) and network • Known duration of (off)peak periods Average facility speed should be realistic. • LOS has to be defined for each network element (e.g., signalized intersection)	• Median versus mean • Different regions have different expected high-concentration traffic hours, making peak periods non-uniform • Upper/lower bound for accepting the average facility measurements	• Using the median value is a more consistent and meaningful practice in performance reporting • Flexibility in defining regional peak periods may be necessary • Use consecutive measurement (e.g., travel time, speed) statistics on a given roadway segment to determine if the reported value is valid. • LOS is not always based on demand to capacity ratio
• Travel Time	• All elements of travel time (TT) such as the TT Index should be defined in a unified and accessible way. • TT must be observed throughout the day • Travel time reliability should be investigated along the route and across the time (i.e., it is route & time dependant)	• Concept of Travel Time Index (TTI) should be easy for the public to understand • Careful consideration of extremely low/high TT (some agencies do not use the top **20%** of the longest travel times) • Missing travel time data • Definition of Normal Travel Time • Definition of Desired Peak Period Travel Time • Definition of Travel time during Non-holiday weekday (used in the calculation of Peak Hour Travel Time)	• Regarding the TTI, certain analogies could be found in the air transportation and adjusted for highway operations • There is a misleading concept which assumes that travel times are consistent with the posted speed limits when data is missing • Normal and Desired Peak Period travel times should be defined in an easily understandable and consistent way • Careful clarification of the observed holiday is needed since it may not be celebrated uniformly across regions

Chapter 5 - Conclusions and Future Directions

The final draft of this report combines the work presented in all three (submitted) Memorandums. The report proposes a consistent and easily accessible framework for organizing information about research and practices for TSM&O performance measurement. The proposed framework is further enhanced with a comprehensive set of performance measurements and strategies from the most relevant and most recent literature. In addition, the proposed framework includes the certain TSM&O strategies and parameters that are less developed and/or difficult to measure. In summary, the proposed framework, enriched with highly beneficial information from the relevant literature, might help practitioners to more successfully adopt specific performance measures.

The adoption of specific measures has to align with the rulemaking under MAP-21 legislation. This report highlights the certain aspects of the proposed framework that will eventually require more attention in this regard. These aspects are closely related to the recent innovation in field operations and need to be defined in a more consistent and easy-to-access/understand way.

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