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16. Abstract

This report describes the year 1 activities on the project titled "Using Operations-Oriented Performance Measures to Support Freeway Management Systems." Work activities included a comprehensive statewide survey on the use of performance measurement, as well as the initial recommendation on both operations and emissions-oriented performance measures to use in support of daily operations.

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OPERATIONS-ORIENTED PERFORMANCE MEASURES FOR FREEWAY MANAGEMENT SYSTEMS: YEAR 1 REPORT

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

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PROJECT BACKGROUND

STATE OF THE PRACTICE IN FREEWAY TRAFFIC MANAGEMENT

The root concept underlying Freeway Traffic Management, as stated in the Freeway Management and Operations Handbook, is to control, guide, and warn traffic to improve the flow of people and goods on limited-access facilities*(1)*.

Traffic management centers (TMCs) typically implement this concept, and traditional operator tasks translate to the following:

- Monitor – observe traffic conditions and watch for abnormal or incident conditions,
- Respond – prepare and initiate actions using field-based infrastructure, and
- Disseminate – assemble and provide information to responders, drivers on the roadway, and the public, using available communication means.

A typical response for managing an incident may be a multi-faceted approach of shutting down a lane, sending an emergency response unit, implementing traffic diversion in the area, and disseminating the information to the local region.

Actions to be taken in response to a situation on the roadway are typically well defined. Effecting a control decision to change the traffic situation is not a decision that is made on a whim. In many TMCs, experienced traffic engineers have created a database of standard response strategies based on such items as type of incident, location, lanes affected, and traffic level. In other locations, experienced operators use historical knowledge and experience to decide what actions to take to respond to a situation on the freeway. In both cases, decisions, and actions, are triggered only by a careful examination and verification of the roadway data.

Once a response is initiated, it is followed to the conclusion and the incident or alarm situation is remedied and traffic has returned to normal patterns. Operators then go back to their normal routine of monitoring the conditions and waiting for the next situation that requires their attention. In most situations, that's where the state of the practice stops for freeway management.

Figure 1 illustrates the state-of-the-practice for traffic incidents. Depending on the location, a ramp may be shut down and lanes on the freeway may be shifted to move traffic out of the affected lane. A message may be posted on a dynamic message sign to convey information to motorists. The response, however, is typically constrained and impacts outside the immediate area do not often enter into consideration. Given the impact area, as illustrated by the rectangle in the figure, the response is more tactical in nature, focusing on the immediate area of the problem.

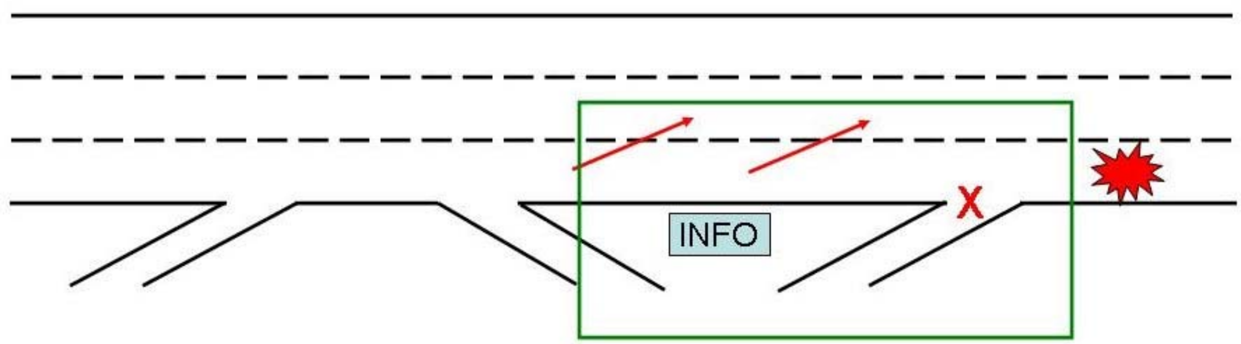

Figure 1. Typical Response Scenario for a Traffic Incident.

This is the typical routine in TMCs operated by the Texas Department of Transportation (TxDOT). In addition to the limited tactical response, little information is kept or retained in a historical file. A lack of data makes it difficult to analyze operator responses to see how, or if, they could be improved in the future.

THE RESEARCH QUESTION

The state of the practice essentially maintains the status quo. Is there an opportunity to improve the state-of-the-practice for responding to traffic incidents? This question is the root issue of this research.

While response scenarios are carefully constructed the first time they are used, there is no feedback mechanism for implementation response to various traffic conditions and for how well the response worked, apart from casual observation by the operator. Across the board, this lack of feedback leads to a fairly static set of response scenarios that are employed in response to dynamic traffic conditions. While some responses may stay the same, other responses may need to be revised to improve traffic operations.

In order to improve the status quo, operators must be able to determine how response scenarios can be improved. Consider Figure 2 as an example. In this response scenario, although the situation is the same as illustrated in Figure 1, the area outside of the immediate impact is now considered as well. This may result in additional ramp actions, actions at the interface point of the frontage road and arterial, a wider dissemination of traveler information, and more. In essence, the response becomes more widespread, or strategic, in nature, as opposed to limited, or tactical.

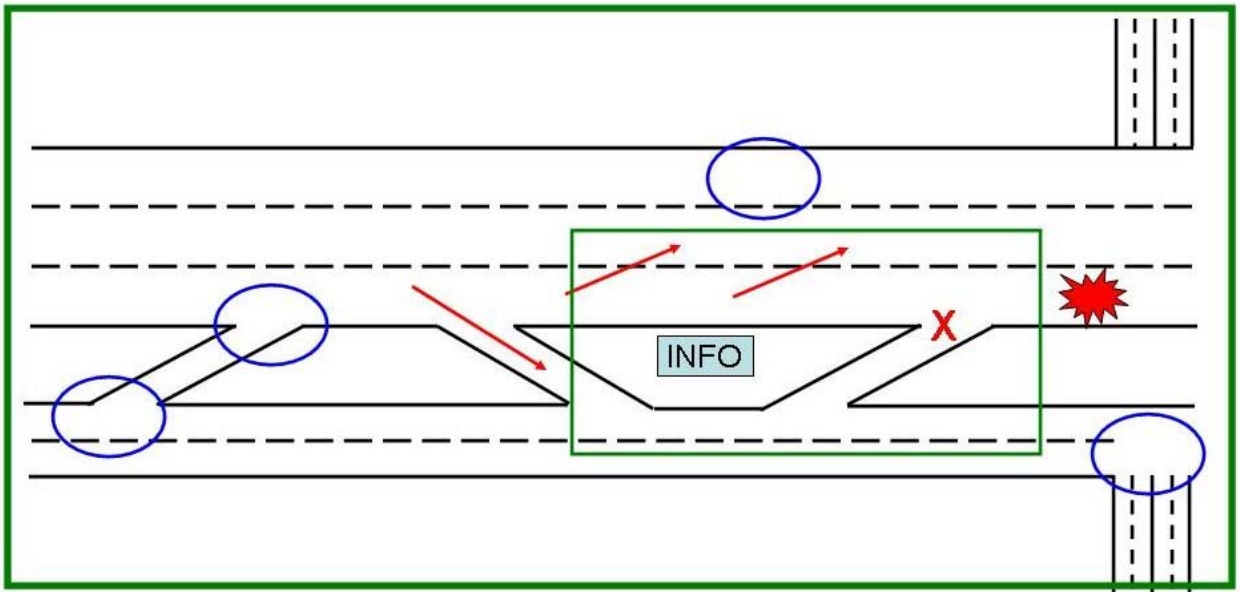

Figure 2. Illustration of a Strategic Response to an Incident.

Thinking and acting strategically requires significant resources. Overall, the level of required information increases. The spatial scale across which that information must be gathered increases. Potentially, the temporal scale for information gathering also increases. In addition, a much broader baseline is also required, to use as a comparison point against any implementation or response.

These general issues raise a number of specific research questions:

- Can the information above, and feedback from the use of a particular response strategy, be used to refine an implementation?
- Could an optimum response strategy be determined from a group of potential strategies, based on the expected response?
- How can roadway operations be improved over the existing, static, tactical response strategies?
- How can the impacts of a given response implemented on the freeway be objectively quantified?

- What procedures or tools can be used to catalog the responses and compare them without bias?
- How should a selection of strategies be made, from a range of possibilities?
- What type of strategies can be incorporated in this approach?
- What are the data requirements for this approach?
- How can TxDOT and TMCs utilize this approach to improve operations?

Overall, the goal of the project is to create a process that can quantitatively analyze an implemented response and provide inputs into an assessment methodology to determine the best response. The goal of the project is not to determine which strategy is most effective in what situation.

THE RESEARCH APPROACH

Traditionally, one of the standard means for assessing the effectiveness of a strategy is to use the concepts of performance measurement. A common definition for performance measurement is "the use of statistical evidence to determine progress towards specific defined organizational objectives" *(2)*.

In other applications, performance measurement is used in real time to evaluate situations such as production line quality. The state of the practice in traffic operations, however, is that performance measurement for real-time operational assessment is not done, other than TMCs that may compute a level of service (LOS) or similar measures, for an operator display. There are no systems in Texas and no known systems nationally where performance measurement concepts are used in combination with an assessment process to determine the benefits of specific implements or provide a mechanism for choosing between multiple strategies.

It is reasonable to examine whether performance measurement techniques could be applied to freeway management as well. The basic assumptions of the research are:

- Performance measurement can be applied to the problem at hand, namely to measure the impacts of changing strategies on the roadway,
- Performance measurement can be used within an assessment methodology to understand the implications of choosing a particular strategy, and
- Performance measurement can be examined for application to both operational and emissions-based strategies.

RESEARCH PROJECT TASKS

To answer the questions, the researchers developed the following nine task workplan:

1. *Assess Methodology for Current Operational Decisions* – capture any performance measurement process in current use.
2. *Determine Operational Performance Measures to Support Freeway Strategies* – prepare a candidate list of operational performance measures.
3. *Determine Emissions Performance Measures to Support Freeway Strategies* – prepare a candidate list of emissions-based performance measures.
4. *Assess Requirements for Performance Measurement Systems* – assess the requirements for utilizing candidate performance measures.
5. *Document Year 1 Progress* – prepare a progress report of project status.
6. *Construct Performance Measurement Based Methodology for Evaluating Multiple Strategies* – develop framework for assessing multiple strategies.
7. *Design Prototype ATMS Displays* – develop prototype screens for utilizing the performance measurement methodology and measures within a advanced transportation management software (ATMS) package.
8. *Develop Concept of Operations* – prepare a document highlighting users, data needs, uses, and data flows for using performance measurement within ATMS.
9. *Document Research Results* – prepare a final, comprehensive project report.

Tasks 1 through 5 were performed in the first year of the research project and are the subject of this report. Tasks 6 through 9 will be performed in the second and final year of the research project.

A BRIEF HISTORY OF PERFORMANCE MEASUREMENT

Prior to detailing the results of the individual tasks, it is important to step back and understand the broad scope of performance measurement. Performance measurement has been applied to numerous applications across many different fields of study. The application of these techniques for real-time traffic operations is the basis of this research. It is appropriate to be aware of the history of performance measurement to gauge how the field has developed to current applications.

WILLIAM DEMING

William Edwards Deming is often stated to be the father of performance measurement. Deming was born in Sioux City, Iowa, in October 1900. He graduated from the University of Wyoming as an engineer and in 1928 completed his studies for a Ph.D. from Yale University. Upon completion of his degree, Deming went to work for the United States government as a mathematical physicist.

Over the course of time, Deming developed both an interest in and understanding of the use of statistical methods to analyze experimental data. He applied these skills in his work at the U.S. Department of Agriculture (USDA) and later at the National Bureau of Standards. He also continued his studies in statistics at University College, the University of London. In 1939, Deming accepted a position as Head Mathematician and Advisor in Sampling at the U.S. Census Bureau in preparation for the 1940 census. The 1940 census was the first census to employ sampling techniques in lieu of the previous approach of counting everyone. In 1943, Deming published a book *Statistical Adjustment of Data* that detailed the application of least-squares regression techniques to various data issues. Leaving the Census Bureau in 1946, Deming became a consultant for statistical studies, which he continued to his death in 1993. At the same time, he also joined the faculty of New York University, lecturing in survey sampling and quality control *(3)*.

In 1947, Deming was asked by the Japanese government to help prepare for the 1951 census. As part of that work, he gave a dozen lectures on statistical and quality control techniques. Combined, these techniques became known as Total Quality Management (TQM). TQM incorporates concepts of product quality, process control, quality assurance, and quality improvement. Deming taught TQM techniques to Japanese industries, most notably the automobile industry. He is credited with significantly helping the country turn around from World War II and embrace the concepts of producing quality products in a new, more global economy *(4)*.

It is important to understand that Deming's work and teachings were not just about statistics or quality control. In reality, the core of his teaching was about management. By embracing what the customer wanted and designing a continuous process to create that product with unsurpassed quality, the focus changed from quotas to customer satisfaction, from results to methods. At the foundation of this continual evaluation of quality was the collection of data gathered by a scientific approach and tools. Deming predicted that adoption of his techniques would significantly improve Japanese market share within five years. History shows that change occurred in some market sectors in as little as four years *(5)*.

Deming's work did not become widely accepted in the United States until the 1980s. Whereas the Japanese industries were focusing on what their customers wanted and then building that with unsurpassed quality, American industries had focused on traditional management methods and the use of quotas and the chain of command. American industries had to embrace TQM as a philosophy that integrates all functions for the sole purpose of meeting customer needs and expectations. The overall process can be viewed as a multi-step path toward better business *(6)*:

1. improve product quality,
2. product costs decrease,
3. employee productivity increases,
4. company (and products) gain additional market share, and
5. company prospers.

As stated previously, the hallmark of this approach was the continual evaluation of quality, using data gathered with scientific methods and tools. Over time, this benchmarking process and the TQM principles became known as performance measurement.

Pictorially, the process can be expressed as shown in Figure 3. Performance measurement becomes the critical link in not only meeting the initial customer focus but also as part of an iterative evaluation from the strategic planning process to keep the customer focus at the forefront of all activities.

Figure 3. Illustration of Management Approach Utilizing Performance Measurement.

PERFORMANCE MEASUREMENT TODAY

Although American industries and agencies were somewhat slower to establish TQM, or performance measurement approaches, over time the concepts have caught on and have been implemented as part of standard business practices.

Federal Government Usage

Perhaps the event that best highlighted the use of performance measurement as a scientific and systematic assessment tool was a benchmark study released by the federal government in 1997 *(7)*. This study advocated the use of performance management across all federal agencies and provided an overview, best practices summary, and framework to assist in that process. Prior even to this study, however, the Chief Financial Officer's (CFO) Act of 1990 required more than 20 major government agencies to appoint a CFO whose responsibilities included periodic systematic performance measurement information, as established by Public Law 101-576. The Government Performance and Results Act of 1993 also required strategic performance and planning initiatives throughout many federal government agencies. The act provided for a 7-year staged implementation of annual performance reporting of performance against goals based on strategic 5-year plans *(8)*. As of result of these pieces of legislation and studies, performance measurement is now an integral part of many federal level government agencies.

It should be recognized, however, that performance measurement is *not* simply the process of collecting data and seeing if a benchmark or value has been met. Rather, performance measurement *is* an overall management system which allows a business or agency to collect and evaluate information for the purpose of achieving goals, increasing efficiency, and meeting customer expectations.

PERFORMANCE MEASUREMENT IN TRANSPORTATION

As in other industries, the use of performance measures in transportation has been common for some time. In fact, many of the basic tenets of transportation, such as capacity analysis, are based on performance measures, although they are not commonly referred to in those terms. The Highway Capacity Manual *(9)* has generally referred to these as measures of effectiveness (MOEs). Density, speed, and volume have all been used as MOEs for different types of analyses. In addition to transportation operations, performance measures are frequently used in other areas of the transportation field, such as pavements, structures, right-of-way (ROW) and utility work, and communications.

In fact, the use of performance measures to analyze systems is of critical importance to transportation. Through consistent application and quantification of these measures, engineers gain the ability to measure and compare situations across different times, areas, and scales.

WIDE-SCALE COMPARISONS

Performance measurement can be used on a wide scale to assess broad patterns and results. One of the best-known wide-scale comparisons utilizing performance measurement data is the Urban Mobility Study, published yearly by the Texas Transportation Institute *(10)*. This study examines congestion across 85 urban areas in the United States utilizing data from 1982 through 2003. The study provides an on-going basis for cataloging and understanding the extent of mobility problems within the United States.

The main performance measure utilized in the study is the Travel Time Index (TTI), which measures the ratio of the time for a trip taken in peak conditions to the time for the same trip in off-peak conditions. As an example, a TTI of 1.4 means that a 30-minute trip in off-peak conditions will take 42 minutes in peak conditions. While the travel time index is the main performance measure utilized, the study includes many such measures and adds new measures over time to help explain the trends in urban mobility.

PERFORMANCE MEASUREMENT IN TRANSPORTATION AGENCIES

The use of performance measurement methodologies by state department of transportation (DOT) agencies has been commonplace for several years. DOTs such as

Pennsylvania, Wisconsin, New York, Texas, and Oregon, to name a few, have long had performance measurement systems in place for various aspects of transportation. For many DOTs, the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 formalized the need for performance measurement by requiring states to implement management systems for several aspects of the transportation system, including:

- pavement management systems,
- bridge management systems,
- safety management systems,
- congestion management systems,
- public transportation management systems, and
- intermodal management systems *(8)*.

As part of the research conducted for National Cooperative Highway Research Program (NCHRP) Synthesis 238, a survey was utilized to collect performance measurement information from state DOTs. The survey sought to identify where performance measurement was being used across all modes of transportation, as well as examine the reporting characteristics in terms of frequency and geographic basis. In particular, information was collected about the following program areas:

- Multimodal Transportation,
- Highway Construction,
- Highway Maintenance,
- Traffic Safety,
- Public Transportation,
- Ferry Service,
- Aviation,
- Railroads,
- Ports and Waterways, and
- Licensing and Registration *(8)*.

Table 1, adapted from Table 1 of the NCHRP synthesis study, shows that as of the 1997 publication date, performance measurement was gaining acceptance in many program areas across the responding states. As might be expected, performance measures were more often associated with traditional programs such as maintenance and construction, but were also being applied to other areas such as licensing and the overall performance of the agency's administration. Table 1 also shows the frequency of reporting that occurs in each of the program areas. It should be noted that some rows may sum to more than 100 percent as a result of reporting at various frequencies.

Table 1. Response Rate and Frequency of Reporting for NCHRP 238 Survey[(a)].

Program Area	In Use by States (%)[(b)]	Frequency of Reporting (%)			
		Monthly	Quarterly	Annually	Other
Multimodal Transportation	28	17	—	92	8
Highway Construction	61	28	8	28	38
Highway Maintenance	89	47	13	60	35
Traffic Safety	83	10	7	83	22
Public Transportation	64	17	22	61	7
Ferry Service	36	62	23	46	15
Aviation	58	42	19	32	19
Railroads	44	22	—	72	6
Ports and Waterways	33	42	17	42	17
Licensing and Registration	28	67	22	33	33
Administrative Performance	36	46	18	46	9

(a) Adopted from Table 1 of Reference *(8)*
(b) Percentages are based on the total number of states (36) responding to the survey.

EXAMPLES OF PRIOR PERFORMANCE MEASUREMENT IMPLEMENTATIONS

An example of an early performance measurement system was the DataLink system constructed at the Texas Transportation Institute *(11,12,13)*. First developed in 1996 and expanded with additional capabilities through 1998, DataLink utilized inductive loop data from the San Antonio TransGuide transportation management center in San Antonio, Texas. At the time of the DataLink system construction, TransGuide operated 26 miles of freeway on three major freeways surrounding the central business district. Speed, volume, and occupancy data were collected from the loops every 20 seconds. Loop spacing was approximately every half-mile in every main-lane. The amount of raw data collected exceeded 100 megabytes per day.

DataLink pioneered a number of considerations related to data management for performance measures. The primary consideration for the system architecture was the data storage requirements. Because of the enormous amount of data being collected, especially for that time frame in computing, appropriate strategies were necessary to keep storage costs within reason. DataLink employed a 5-minute aggregation routine to reduce the storage requirements by approximately 93 percent.

In a similar consideration to the size of the overall storage, the desired storage and retrieval capabilities necessitated the use of a relational database. Common desktop databases could not handle the requirements of the system, and a larger enterprise-level database was utilized. Specialized screening rules were developed to ensure data integrity within the database. Performance measures identified the number of data elements used in the calculation to ensure proper interpretation of the results.

The ability to easily access and work with the data contained in the database was a crucial factor in making the system feasible. DataLink utilized an open-standards web interface to provide access to and manipulation of the data within the system, eliminating the need for specialized programming or database skills on the part of system user and expanding the ability to use the system to anyone in the target agency. This highlights a key finding related to performance measurement: The data should be available to those who need to use it and it should not be difficult to find or develop.

In its most basic capabilities, DataLink output provided speed, volume, and occupancy information at user-specified time intervals and locations. The aggregation techniques provide a report on time periods from 5 minutes to 1 day. DataLink output also supported the calculation of performance measures based on both lane and corridor aggregation techniques.

The DataLink system was research-based and explored a number of never-before examined questions pertaining to large-scale data archiving activities within transportation. A similar, but operational, system was constructed in Montgomery County, Maryland *(14)*. Known as DASH, or Data Acquisition and Hardware, the system utilized many of the same components as DataLink. The system employed screening techniques for data integrity, automatically updated itself as new detectors were brought on-line, updated new data once a day, and allowed multiple end-user queries. DASH provided significant benefits to Montgomery County, including the ability to collect and store more accurate and precise data, improve information sharing throughout the agency, and reduce the need for supplementary traffic data collection.

Throughout the literature, a number of smaller-scale systems used performance measures constructed from archived data to analyze more focused objectives. One such study performed travel time analyses on the Katy Freeway in Houston, Texas *(15)*. The objective was to quantify travel any time savings on the toll lanes as compared to the main lanes. This study was not a large-scale exercise but allowed development of an evaluation procedure and framework for using the travel time savings information as a performance measure.

FACTORS AFFECTING THE USE OF PERFORMANCE MEASUREMENT IN TRANSPORTATION

While the data are a critical element of any performance measurement system, the literature also shows other factors which must be considered. One critical factor in the application of performance measurement is the geographic scale. Performance measures can be constructed to look at global objectives, to focus on a detailed evaluation of any given component of the transportation system, or to examine any level in between. Table 2 lists the geographic scales used by transportation agencies reporting results to the survey in NCHRP 238.

Table 2. Geographic Basis for Reporting Performance Measures in NCHRP 238 Survey[(a)].

Program Area	Frequency of Reporting[(b)] (%)			
	Statewide	Regional/District	County	Urban/Local
Multimodal Transportation	58	25	25	25
Highway Construction	72	28	6	6
Highway Maintenance	69	52	28	3
Traffic Safety	81	20	22	17
Public Transportation	48	11	24	28
Ferry Service	15	31	8	15
Aviation	77	7	—	13
Railroads	78	—	—	6
Ports and Waterways	50	25	—	8
Licensing and Registration	89	22	22	22
Administrative Performance	73	36	—	—

(a) Adopted from Table 2 of Reference *(8)*
(b) Percentages are based on the total number of states (36) responding to the survey.

As can be seen, many of the areas of measurement had widespread applicability across large geographic regions, such as statewide or across a region. The geographic scales and percentages listed above may also be skewed by the program areas in the survey. Other areas, such as incident management, may focus on smaller areas or aspects of the transportation system. This concept of scale is critical to not only understanding but properly applying performance measurement to transportation.

PERFORMANCE MEASURES FOR TRANSPORTATION OPERATIONS

Perhaps the aspect of transportation that has the largest impact on the daily lives of users of the transportation system is that of operations. Transportation operations is a vast area of programs and policies designed, in large part, to address the congestion on the nation's highways and improve the traveling conditions. Transportation operations include areas such as:

- arterial management,
- access management,
- congestion mitigation,
- corridor traffic management,
- emergency transportation operations,
- freeway management,
- freight analysis and management,
- real-time traveler information,
- road weather management,
- tolling and pricing opportunities,
- traffic analysis and simulation,
- travel demand management,
- traffic incident management,
- planned special events traffic management, and
- work zone management *(16)*.

Despite the large number of programs and resources devoted to operations, Table 1 and Table 2 show that performance measurement is not in common use in this area.

LEVELS OF PERFORMANCE MEASUREMENT IN OPERATIONS

Similar to the other areas of transportation, the application of performance measurement to operations can incorporate multiple scales or levels. Figure 4 [adopted from Figure 1-1 of Reference *(17)*] illustrates this concept by showing a pyramidal approach to defining performance measures. At the top of the figure is the largest level or area of measurement, the system-wide assessment. This is the most global view of operations and serves a multitude of purposes. For one, this may be the information that the public and elected officials receive on a consistent basis, identifying the state of the overall transportation system and the progress the agency is making in operating it in an efficient manner. These types of system-wide assessments may be instrumental in focusing funds and personnel on critical priorities.

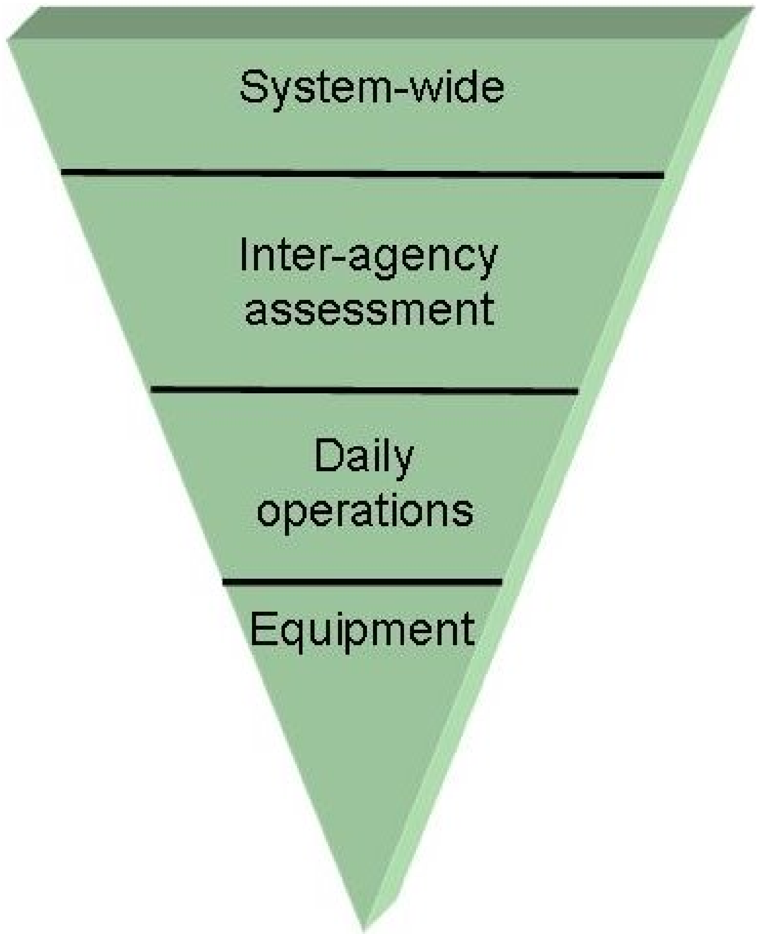

Figure 4. Multi-Level Approach to Operational Performance Measures.

The next step down in the pyramid is inter-agency assessment. Many operational programs, such as incident management, congestion mitigation, air quality, and more, are joint efforts between multiple agencies. The performance measures at this level focus on defining how these programs are working and if the various resources are being used effectively to bring significant improvement to the program. The focus area of these programs is typically smaller than the entire system. Example focus areas may be on a specific corridor or known problem area.

The next level in the figure is daily operations. The focus here is the day-to-day efforts that operators perform in a TMC. On a routine, daily basis, operators determine and execute responses based on inputs and execute strategies to keep traffic flowing. These responses and strategies may be lane shifts, dynamic message sign postings, implementing changes in ramp operations, or more. While the focus area of these actions is typically compressed, i.e., smaller than an entire corridor, the potential impact area is much larger.

At the bottom of the pyramid are those measures that focus specifically on equipment or very discrete elements of the transportation system. Typical applications at this level may include items such as up-time, reliability, integrity of data, or more. Looking at these measures should provide an overview sense of how the data collection, processing, storage, and calculation components of performance measurement are working across the entire extent of transportation operations.

OPERATIONAL PERFORMANCE MEASURES USED IN TEXAS

In the current state-of-the-practice, the use of performance measurement techniques within TxDOT is minimal. Some areas use system-wide measures to convey information to the public or elected officials. This is typically done as some sort of annual summary of conditions or progress report.

Another implementation of performance measures is within TMC software. Although the software varies by TMC, a typical installation examines data from the roadway and reports speed, volume, and occupancy as basic indicators of performance. Figure 5 shows a screen capture from the TxDOT ATMS utilized by TxDOT in many of its TMCs.

As seen in the figure, operators can look at the volume at varying levels of aggregation. Inductive pavement loops typically report data every 20 to 30 seconds. Aggregation combines data into larger time intervals for display to, and interpretation by, operators. Figure 5 also shows speed and occupancy values across different detector stations. The TxDOT ATMS also displays LOS measures for each segment of the roadway, which is based on a calculation of density.

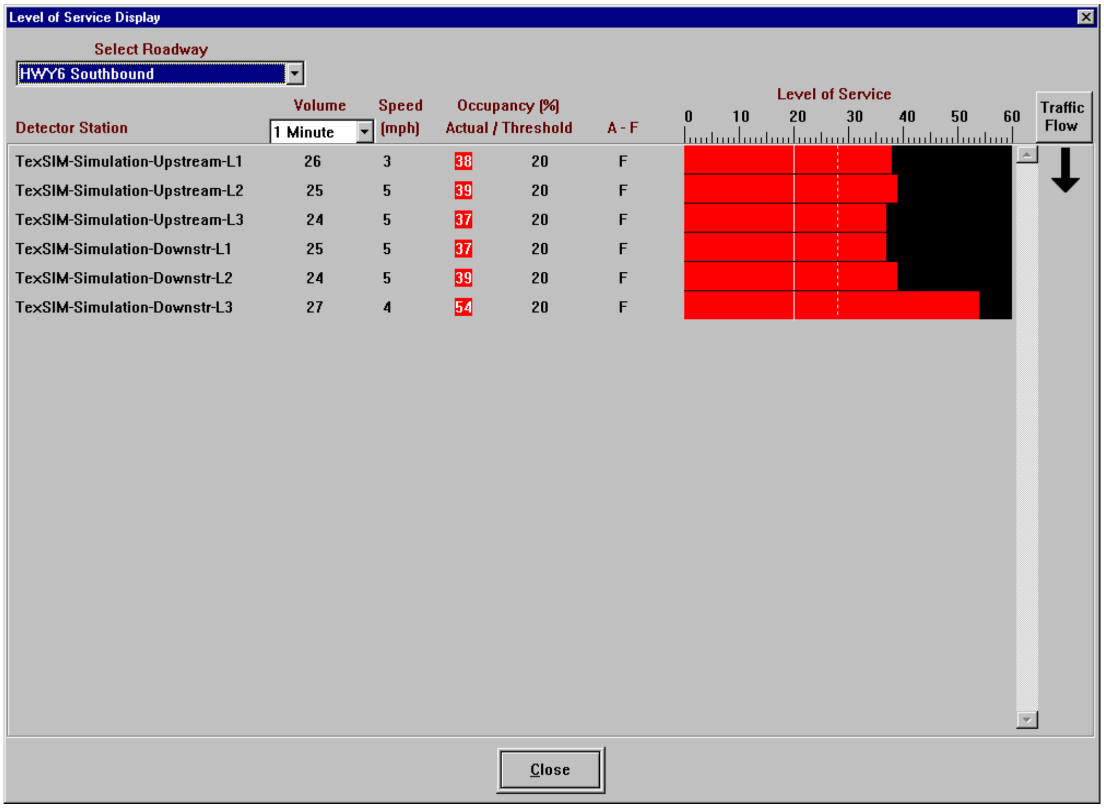

Figure 5. Use of Performance Measures in TxDOT ATMS.

PERFORMANCE MEASUREMENT QUESTIONNAIRE

Apart from these situations, the use of performance measurement techniques within the department is not well known or documented. In order to obtain complete information pertaining to the overall usage of performance measurement techniques, researchers developed a questionnaire to determine if, how, and where performance measurement was being used in Texas.

The questionnaire consisted of questions in seven topic areas:

1. Overview of Performance Measurement
2. System-Wide Assessment – Operations
3. Program (Inter-Agency) Assessment – Operations
4. Daily Operations Assessment – Operations
5. Equipment/Facilities Assessment – Operations
6. Emissions Based Performance Measurement
7. Closing Comments/Remarks

The survey was administered via face-to-face or telephone interviews to six locations within Texas, including:

- TransVista (El Paso),
- TransGuide (San Antonio),
- TranStar (Houston),
- DalTrans (Dallas),
- TransVision (Ft. Worth), and
- TxDOT Traffic Operations Headquarters (Austin, TX).

Each survey respondent was contacted initially via telephone or electronic mail and asked to participate. The respondents were given an overview of the questionnaire and told that it would take approximately 30 minutes to go through the questions. A scheduled time for the interview was then set according to the schedule of the respondent.

These sites and their answers to the questionnaire provided a comprehensive look at the use of performance measurement in Texas. Each of the following sections presents the questions from the questionnaire and an overview of the results

Overview of Performance Measures

The scope of this section of the questionnaire was to introduce the concept of performance measurement and get an understanding of where the respondent stood in terms of knowledge of the subject and application of the general concepts within their agency

The specific questions asked in this section are shown in Table 3. The table lists the question, as well as the type of response that was set up in the questionnaire. Freeform indicates that the respondent was provided space for an answer that was not constrained by a set of pre-determined responses.

Table 3. Questions Asked in Part 1 of Performance Measurement Questionnaire.

Number	Question	Type of Response
1	What types of operational freeway management strategies are currently in use?	Freeform
2	What types of emissions based freeway management strategies are currently in use?	Freeform
3	Do you know about Performance Measurement?	Yes / No
4	Do you currently use performance measurement?	Yes / No

Number	Question	Type of Response
5	Where are performance measures being used within the context of your daily operations? Where do you see them being applicable in the future? (Check all that apply)	Multiple choice: (Current / Future) • System-wide Assessment • Program (Inter-Agency Assessment) • Internal (Intra-Agency Assessment) • Equipment
6	What is the main motivation for using performance measurement?	Multiple choice: (Yes / No) • Legislative Mandate • Agency-wide Initiative • Local/District Initiative • Competing for Scarce Dollars • Communications to External Agencies • Communications to Customers • Other (specify)
7	Do you currently use performance measurement in support of any of the strategies identified above in Questions 1 or 2?	Yes / No
7a	If yes, could you please identify which strategies?	Freeform
7b	If no, are there any strategies which you are planning to support via performance measurement or would like to do so in the future?	Freeform
8	Do you have a formalized procedure for collecting, calculating, and applying performance measurement?	Yes / No
8a	If yes, could you explain your process in more detail?	Freeform
9	If Performance Measurement will not be used, could you please explain why?	Freeform
10	Does / would Performance Measurement make your job easier or harder?	Multiple choice: • Harder • Easier • Not Sure
10a	If "harder," please explain.	Freeform
11	Does your control center software support performance measurement?	Yes / No
11a	If not, will it in the future?	Yes / No
12	Is Performance Measurement covered in your operations manual?	Yes / No
12a	If so, could we get a copy of the applicable sections?	Yes / No
12b	How often are the performance measures in use revisited?	Timeframe

Overview Summary

Respondents indicated that a wide variety of strategies are being employed in support of freeway management. These include:

- multi-agency incident management,
- corridor management,

- co-location of agencies,
- public information/outreach,
- dynamic message signs,
- lane control signals,
- data archiving,
- weather responsive condition alerts,
- high-occupancy vehicle/high-occupancy toll (HOV/HOT) lanes,
- ramp metering,
- traffic management centers,
- equipment maintenance database, and
- construction impact management.

The type and extent of the responses are a testament to the breadth of techniques being employed across Texas to help manage and mitigate traffic situations. In contrast, for emissions strategies, respondents indicated that a significantly smaller set of strategies is in use. The predominant answer was ozone alert days. Even with this strategy, there are no real numbers to support the strategy.

In general, while respondents indicated that they knew about performance measurement, the majority said that it was not in use within their particular agency. Figure 6 shows that currently the predominant use is for either system-wide or program level assessments. These were reported to be items such as an annual benefits report or assessment of incident monitoring programs. Respondents indicated that in the future, they would like to use performance measurement concepts in support of activities such as real-time impact analysis, improved regional coordination, and real-time monitoring. One agency indicated that performance measurement concepts would shortly be in use for equipment monitoring, as it was being written into their support contract.

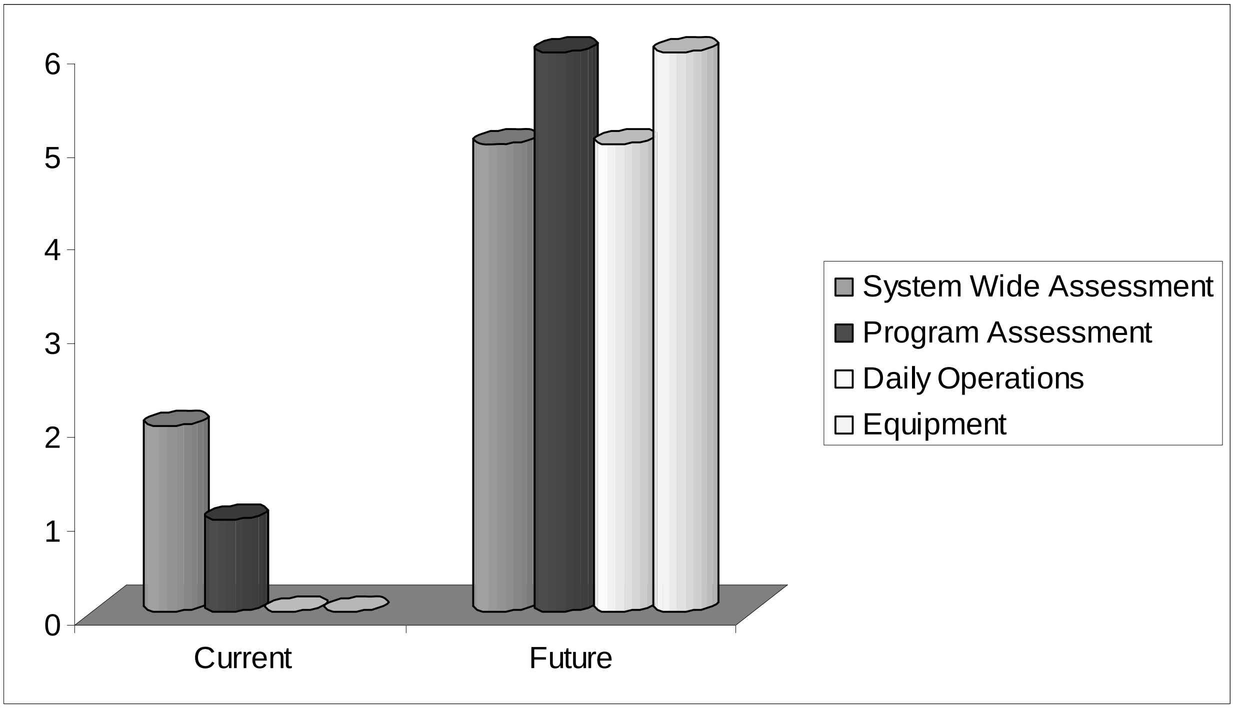

Figure 6. Current/Future Areas of Performance Measurement Use.

Figure 7 shows a tabulation of the motivations reported for using performance measurement. Note that the number of respondents was not the same for every category. For this reason, the tabulation displays raw responses instead of percentages. The figure reveals that the predominant reason for using performance measurement is not a legislative or agency-wide mandate but rather local initiatives, to increase and improve communications and as a way of assessing operations.

Question 8 asked if respondents had a formalized procedure for collecting, calculating, and applying performance measurement. Affirmative answers received were for data collection only. No respondents had a process in place for calculating and applying performance measurement.

In a similar vein, no respondents have performance measurement in their operations manuals. Currently, the majority of software in use across the state does not support performance measurement, although respondents indicated their belief that it would be supported in the future.

Sixty percent of the respondents indicated that performance measurement would make their job easier, as it would provide quantifiable justification to support decisions. Dissenting opinions voiced the concern that while performance measurement might make operations more effective, it could also cause additional work, making the overall job harder.

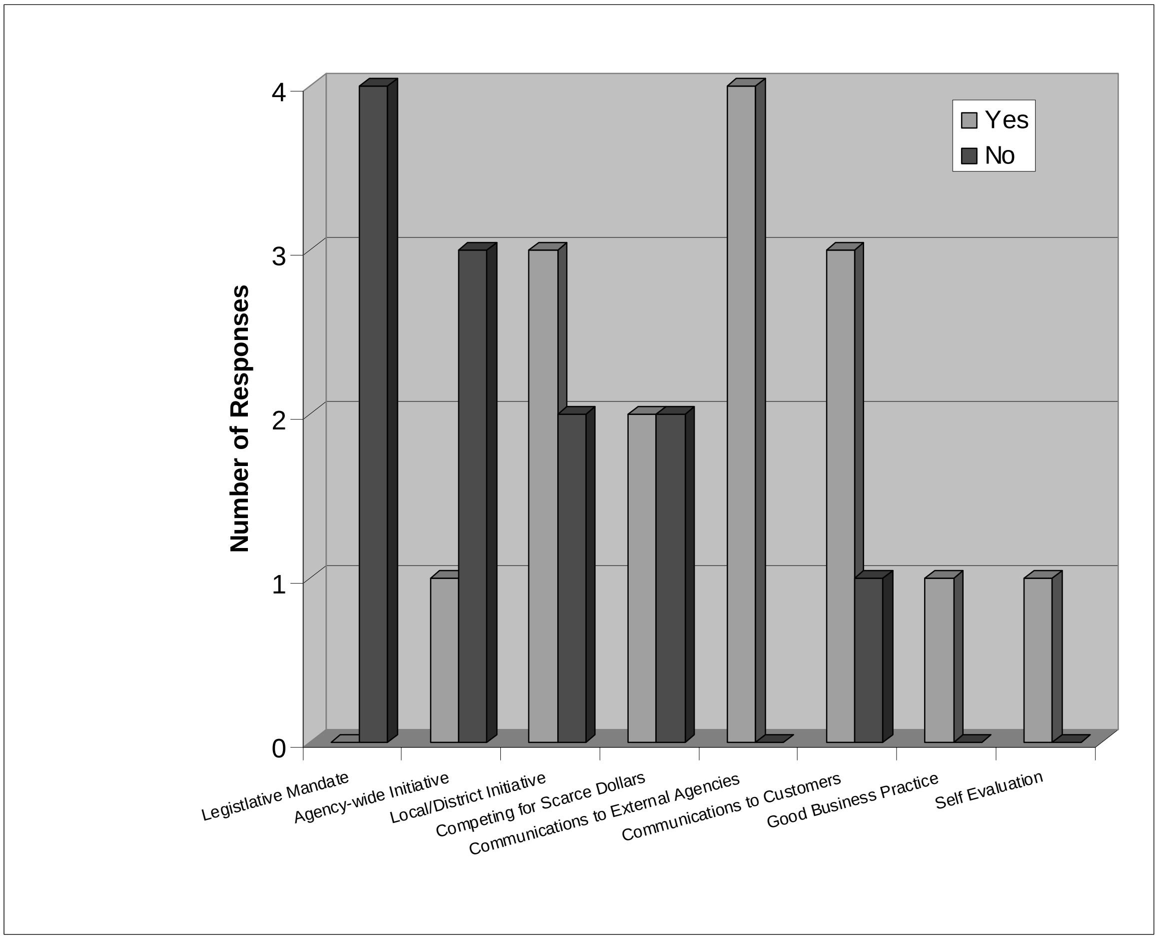

Figure 7. Motivation for Using Performance Measurement.

System-Wide Assessment – Operations

The scope of this section of the questionnaire was to determine the usage of performance measurement in support of system-wide assessments. This is the highest level of looking at operations and serves a multitude of purposes, including public information, system reporting, summary of annual benefits, and similar uses. These types of system-wide assessments may also be instrumental in focusing funds and personnel on critical priorities, or obtaining funds by highlighting a need.

The specific questions asked in this section are shown in Table 4.

Table 4. Questions Asked in Part 2 of Performance Measurement Questionnaire.

Number	Question	Type of Response
1	Do you currently use system-wide operational-based performance measurement for any type of strategy assessment or strategy implementation?	Yes / No
1a	If not, would you like to in the future?	Yes / No
2	What is (would be) the overall goal of using Performance Measurement to support this area of use (mandate, perception, expectations, make case for funding, etc.)?	Freeform
3	Can you identify the particular measures (in use currently or future desired)? (use the chart on the next page)	Freeform via chart
4	What are your future plans for the use of performance measurement in this area?	Freeform

Question 3 is the mechanism for obtaining detailed information pertaining to any specific performance measures in use at the system-wide level. The question refers to a table format (illustrated in Table 5) and asks for the following information:

- area,
- goal,
- objective,
- measure,
- target,
- target rationale (if any),
- qualitative or quantitative,
- data needs,
- customer,
- focus area,
- timeline,
- when performed (i.e., time lag from current data),
- automatic mechanism in place?, and
    - collection (Yes / No)
    - calculation (Yes / No)
    - assessing (Yes / No)
- who performs assessment?

Table 5. Example Table for Listing Sample Performance Measures.

Area	***Goal***	***Objective***	***Measure***	***Target***	***Target Rationale (if any)***	***Qualitative/ Quantitative***	***Data Needs***	***Customer/ Focus Area***	***Timeline***	***When Performed (i.e. time lag from current data)***	***Automatic Mechanism in Place?***			***Who Performs Assessment?***
											Collect	***Calculate***	***Assess***	

Researches requested these information items as direct support to future tasks in the project.

System-Wide Assessment Summary

The responses to this section of the survey indicated that for the most part, performance measurement to support system-wide assessments is not being used. This corresponds to Figure 6, which indicated only a few current users. Measures that respondents indicated as being in use include:

- travel time,
- travel speed,
- total delay,
- recurrent delay,
- no-recurrent delay,
- travel time index, and
- incident detection rate.

In general, the overall goal of using performance measurement for this area was to evaluate actual performance against expectations, justify funding, or modify procedures to improve the system.

Program (Inter-Agency) Assessment – Operations

The scope of this section of the questionnaire was to determine the usage of performance measurement in support of program level, typically inter-agency, type of operations. Performance measures at this level focus on defining how a program is working and if the various resources are being used effectively to bring significant improvement to the program. The focus area of these programs is typically smaller than the entire system and may focus on a specific corridor or problem area.

The specific questions asked in this section are shown in Table 6. Note that the questions mirror those of the previous section, with slight wording changes.

Table 6. Questions Asked in Part 3 of Performance Measurement Questionnaire.

Number	Question	Type of Response
1	Do you currently use performance measurement to support any type of program level (intra-agency) assessment?	Yes/No
1a	If not, would you like to in the future?	Yes/No
2	What is (would be) the overall goal of using Performance Measurement to support this area of use (mandate, perception, expectations, make case for funding, etc.)?	Freeform
3	Can you identify the particular measures (in use currently or future desired)? (use the chart on the next page)	Freeform via chart
4	What are your future plans for the use of performance measurement in this area?	Freeform

A table similar to Table 5 was also provided to respondents to capture any specific performance measures being utilized.

Program Level Assessment Summary

The responses to this section of the survey indicated that for the most part, performance measurement is not being used in support of program level assessments. All of the respondents indicated its potential to be a worthwhile tool in the future as well as their willingness to use it, given the proper tools. One respondent indicated that one use would be to monitor partner effectiveness. No sample measures or supporting information was received.

Daily Operations Assessment – Operations

The scope of this section of the questionnaire was to determine the usage of performance measurement in support of daily operations. Performance measurement would be used in this area as an analysis tool for looking at the benefits of a particular action or strategy.

The specific questions asked in this section are shown in Table 7. Note that the questions mirror those of the previous section, with slight wording changes.

Table 7. Questions Asked in Part 4 of Performance Measurement Questionnaire.

Number	Question	Type of Response
1	Do you currently use performance measurement to support any type of internal program assessments?	Yes/No
1a	If not, would you like to in the future?	Yes/No
2	What is (would be) the overall goal of using Performance Measurement to support this area of use (mandate, perception, expectations, make case for funding, etc.)?	Freeform
3	Can you identify the particular measures (in use currently or future desired)? (use the chart on the next page)	Freeform via chart
4	What are your future plans for the use of performance measurement in this area?	Freeform

A table similar to Table 5 was also provided to respondents to capture any specific performance measures being utilized.

Daily Operations Assessment Summary

No respondents reported the use of performance measurement at this level. Problems cited during the interviews included a lack of support of software, no standard operating procedures, and the tremendously large number of potential measures. The majority of the respondents indicated a willingness to use performance measurement in this area in the future but expressed a desire to see significant direction from TxDOT on what to use, at least as a starting point or minimum set of measures.

Equipment/Facilities Assessment – Operations

The scope of this section of the questionnaire was to determine the usage of performance measurement in support of equipment and facilities assessment. This is generally the lowest level of performance measurement and can be used at the level of an individual piece of equipment to track items such as maintenance needs, up-time, response time, error indications, and more. Performance measurement at this level can also be used to track the functioning of a particular system, even if the system comprises multiple components.

The specific questions asked in this section are shown in Table 8. Note that the questions mirror those of the previous section, with slight wording changes.

Table 8. Questions Asked in Part 5 of Performance Measurement Questionnaire.

Number	Question	Type of Response
1	Do you currently use performance measurement to support any type of equipment or facilities assessments?	Yes/No
1a	If not, would you like to in the future?	Yes/No
2	What is (would be) the overall goal of using Performance Measurement to support this area of use (mandate, perception, expectations, make case for funding, etc.)?	Freeform
3	Can you identify the particular measures (in use currently or future desired)? (use the chart on the next page)	Freeform via chart
4	What are your future plans for the use of performance measurement in this area?	Freeform

A table similar to Table 5 was also provided to respondents to capture any specific performance measures being utilized.

Equipment / Facilities Assessment Summary

Some respondents reported working toward the use of performance measurement in this area. In particular, one respondent indicated that performance measurement and specific targets were being written into a new maintenance contract. Performance measurement can also be used to assess equipment readiness, especially for emergency situations such as evacuations. The long-term plans for this respondent included tracking maintenance characteristics by equipment type, by vendor, and by service agency to ensure the best performance and response for the taxpayer dollar.

Emissions-Based Performance Measurement

The scope of this section was to determine if performance measurement was being used in support of any particular emissions strategies across the state. The difficulty of using performance measurement in support of emissions strategies is two-fold. First, the measurements are not taken in real time from point sources, rendering it difficult to be reactive to changes in the air quality environment. Second, because many areas in addition to transportation contribute to air quality, assessing the impact of specifically transportation and crafting strategies to reduce those impacts is also quite difficult.

The specific questions asked in this section are listed in Table 9.

Table 9. Questions Asked in Part 6 of Performance Measurement Questionnaire.

Number	Question	Type of Response
1	Do you currently use emissions-based performance measurement for any type of strategy assessment or strategy implementation?	Yes/No
1a	If not, would you like to in the future?	Yes/No
2	What is (would be) the overall goal of using Performance Measurement to support this area of use (mandate, perception, expectations, make case for funding, etc.)?	Freeform
3	Can you identify the particular measures (in use currently or future desired)? (use the chart on the next page)	Freeform via chart
4	What are your future plans for the use of performance measurement in this area?	Freeform

A table similar to Table 5 was also provided to respondents to capture any specific performance measures being utilized.

Emissions Summary

Overall, respondents wanted to reduce emissions by reducing congestion and reducing incident clearance time. However, respondents cited the difficulties of supporting those desires with current data collection and equipment. In addition to the difficulties previously expressed, cost and maintenance of collection equipment was also seen as a significant hindrance toward widespread usage of this aspect of performance measurement.

Closing Comments/Remarks

The final section of the questionnaire was a freeform response to give the respondents an opportunity to provide any additional thoughts or comments.

The specific questions asked in this section are shown in Table 10.

Table 10. Questions Asked in Part 7 of Performance Measurement Questionnaire

Number	Question	Type of Response
1	Do you have any closing comments or remarks on the use of performance measurement to support operational strategies?	Freeform
2	Would you like to receive a notice of publication of the survey results and final report, when complete?	Yes / No

Closing Comments Summary

Only two respondents had any additional comments for this section, as most of the information was offered in previous sections. The comments received indicated support for the research and a desire to participate in efforts in this area in the future.

IMPLEMENTING PERFORMANCE MEASUREMENT

PERFORMANCE MEASURES IN DAILY OPERATIONS

As stated in the introduction, the overall goal of this research project is to construct a framework that can quantitatively analyze an implemented response and provide inputs into an assessment methodology to determine the best response. This puts the focus squarely on daily operations as the appropriate level for this framework to be developed.

The questionnaire clearly showed that across the state, while performance measurement is understood and appreciated for what it could provide to transportation operations, implementation to date is minimal. This was especially true in the arena of daily operations, as there were no respondents utilizing performance measurement.

One of the critical inputs for effective use is choosing what measures should be used. This is a significant challenge for daily operations, as literally thousands of measures could be identified to represent a particular emphasis or strategy or capture a particular response. It is impossible, however, to implement all of the measures without creating an incomprehensible system of data collection, storage, and analysis techniques. What is therefore required is a minimal but comprehensive set of measures that can be used in daily operations to effectively analyze actions and respond appropriately to changes. A literature review was performed to determine what lists of measures have been used external to TxDOT and if there are recommended measures for daily operations.

TYPES OF PERFORMANCE MEASUREMENT

Input/Output/Outcome

Performance measures may be classified in any number of ways. One of the simplest methods of classification is to identify each measure as an input, output, or outcome.

An input measure examines the resources available to carry out a program. The selection of the performance measure may be difficult to evaluate if the input parameter is difficult to obtain. One example might be the number of vehicles that enter a corridor that is supported by a Traffic Management Center

An output value is usually a quantitative value that is based on a tabulation calculation or measurement. One example of an output performance measure is the travel time through a corridor or segment of highway.

An outcome variable is usually more subjective. An outcome performance measure provides an assessment of the results of a traffic management tool or strategy or institutional program. The outcome answers the effectiveness of the current program.

In many cases, a performance measurement system may use measures from all three areas. One example is the effectiveness of the number of incident management response teams on the amount of clearance time along Interstate 10. In this example the input is the number of response teams and the output is the average time to clear an incident along I-10. The output may be that the increase in incident response teams improved the incident clearance time by 10 percent, saving the motorists more than one million dollars per year. As a result of the input and the output, this theoretical case would be considered an effective institutional policy for improving incident clearance times.

Goal-Based Classification

Performance measures may also be evaluated based on the goals of the program. Identifying the goals helps to provide a continual focus for the agency of the TMC. In this classification system, the performance measure should help to determine the progress of the program in relationship to the overall goals and/or objectives of the system. Some goals commonly used in this type of performance measure classification include:

- Accessibility – ensuring convenience and or right-of-entry to customers;
- Mobility – relative ease of difficulty of making a trip;
- Economic Development – cost, economic health, and vitality of the transportation system;
- Quality of Life – sense of community desires and customer satisfaction;
- Environmental and Resource Conservation – assets saved or expended, wither natural or man-made;

- Safety – levels and rates of incidents or other occurrences;
- Operational Efficiency – productivity, manpower, financial resources, etc; and
- System Condition and Performance – physical conditions, service ranges, etc.

It is not uncommon for a goal-based system to use a secondary classification scheme. Mobility, for example, may be divided into passenger or freight mobility. Safety may be divided into roadway, rail, transit, parking, pedestrian, freight, and more. In some cases, the secondary classification does not need to be consistent with the overall framework of the program. The secondary classification may provide information across multiple performance measures and in some cases, the secondary classification may have a greater impact on one of the performance measures. One example of this last case may be the impact of vehicle speed. In one case vehicle speeds are very fast and travel time and overall mobility is efficient. However, under this theoretical example the number of crashes increases exponentially and lowers the safety of the corridor. In this case the final goal of secondary classification needs to be analyzed or weighted by the local staff.

CHALLENGES OF PERFORMANCE MEASURES

The results of the literature reviews, the TxDOT questionnaire, knowledge of ATMS software, and casual observation of web sites clearly indicate that the majority of agencies are still using the most basic performance measures to describe freeway operations.

One potential reason is that assessing operational performance is still a relatively new area. Data needs for calculating measures beyond the basics may not be supported by existing infrastructure and ATMS programs. Because the use of supplementary measures may involve additional data collection or software development, significant cost may be involved in migrating toward more sophisticated measures.

A second potential reason why basic measures are used is that the variety of available performance measures is large. As an example, consider the measurement of congestion. Performance measures related to congestion may be based upon :

- Duration – focus on the temporal limits of the congestion,
- Extent – focus on the geographic limits of congestion,
- Intensity – focus on the severity of the congestion, or
- Reliability – focus on the variation in the congestion *(2)*.

The number of different measures that could be used to describe a single concept (such as density) may be very confusing to different audiences, perhaps most especially to the traveling public. The need to communicate exactly what the measures describe is an impediment to their wide-scale acceptance and use.

A third potential reason why more sophisticated measures are not used may be the data necessary to support their use. Many of these more sophisticated measures require a baseline—a point of comparison for understanding normal conditions. This comparison requires collection, storage, and availability of roadway data for comparison use.

Consider the use of speed as a performance measure. It is generally well understood and because it provides an indication of the system at a specific location and point in time, it requires no reference point. In comparison, consider the use of queue length after an incident. In order to be effective, this performance measure has to be examined over time. Is the queue length decreasing or increasing? How far back from the incident does the queue start? Analyzing these performance measures may provide a more detailed understanding of an incident and the operational response necessary to clear it from the roadway, but it requires a baseline in time and space that translates to extensive data needs.

The archival of data to support this need is not an insignificant task. The roadway infrastructure generates a tremendous volume of data. As an example, consider that the 26-mile phase one deployment in San Antonio, Texas, generated nearly one gigabyte of raw data per day *(14)*. While that amount is not as difficult to deal with as it was even five years ago, expanding the coverage area to three or four times the of phase one deployment and keeping the data for a year would result in the need for more than a terabyte of space. That amount of data storage can be costly and is certainly not a trivial matter to incorporate into an archive data library. Also, the time required to process and perform calculations using that much data must be considered in any system design.

As operational performance measurement becomes more commonplace, programs will begin to employ a broad spectrum of measures to capture all of the various facets of program use. NCHRP 446 *(19)* discusses the differentiation of output and outcome performance measures. Output measures are indicators of resources utilized or perhaps the scope of activities performed. Output measures identify information about the management of resources and are most useful in a performance-based system. In contrast, outcome measures are often more indicative of how well an agency meets its goals and objectives. Outcome-based measures are more likely to be significant and understandable to the general public. However, both types of measures are useful, and a successful performance measurement system generally includes both.

Consider, for example, an area of concern related to safety in icy conditions. An output measure might be the number of tons of salt applied to the roadway. While this measure has a majority of the 10 characteristics listed above and is easily understood and measured, it is most applicable to the agency in charge of the roadways. The corresponding outcome measure might be the number of ice-related accidents. This measure is much more easily understood by the traveling public and can be shown over time and large areas to highlight improvements to the system. Both types of measures work in conjunction with one another to provide a complete analysis and evaluation of the system *(19)*.

In addition to looking at the factors discussed above, determination of the appropriate performance measures also requires consideration of other aspects of the system. One important consideration is who will be using the measures. A number of different types of activities take place in a transportation environment, from planning and design to operations and maintenance. Careful consideration of each of these specific needs creates a stronger success potential for a performance measurement system. Performance measurement systems should also consider users beyond the general public. These can include elected officials, the media, and users in the judicial system, to name a few *(20)*.

Another consideration is the increasing assessment of the multi-modality of transportation systems. As such, measures that concentrate on the mobility of the entire system, rather than a specific node, may prove to be very useful and necessary. Mode-specific measures may be used in conjunction with the multi-modal approach to identify any deficiencies and to determine individual mode effects.

What Makes A Good Measure?

First and foremost, a performance measure must measure or gauge the right item. It does so by focusing on the goals and objectives and determining if they are being met. A performance measure should focus on the end result—not the measurement itself.

The second trait of a good performance measure is that it is accepted. Generally, this means that the measure must be simple, understandable, unambiguous, and meaningful to the customer, regardless of who the customer is. To best accomplish this, agencies may use different measures for different customers.

The third trait is that performance measures must be responsive and/or sensitive to the data they measure. They do this by clearly showing trends, changes, minimums, or maximums. A performance measure that is insensitive to these events within the data will not be meaningful to the customer because it cannot accurately depict progress toward the system goals.

The fourth trait of a good measure is that it is appropriate. Judging the appropriateness of a selection is typically done in two ways. First, the measure must be temporally appropriate. If the desire is to determine a percent reduction in incidents, the measure should look at a lengthy analysis period, such as a week, a month, or even a year. Reporting on a time frame of minutes, hours, or even a day would make little sense and would be an inappropriate time frame for this measure. Second, the measure must be geographically appropriate. Measures can be directed toward a point, a segment, an entire facility or travel corridor, or even a region. A reduction in travel time would not make sense at a point location but might be a good measure from a corridor or regional perspective.

A fifth and somewhat arguable trait is that a good performance measure should be supportable by economical data collection. Measures that require large and expensive data collection are not likely to be determined very often, due to time and/or budgetary constraints. This makes the measure untimely and insensitive to smaller changes, and ultimately it will not convey meaningful results. At the same time, TMCs should recognize that it is OK to stretch beyond the current practice and find and collect additional data sources, if the performance measures can provide meaningful results. This trait is arguable because many agencies have fallen into the trap of only looking at measures that can be supported by data they already collect. This can hinder effective evaluations and often results in choosing measures that do not support the stated goals.

Keys to a Successful Program

Over time, researchers have identified a number of keys to having a successful performance management program. These keys, listed below, are not set in stone but provide some guiding principles to help organizations navigate through the chore of picking appropriate measures. These keys are not an exhaustive list from the literature but rather a compilation of those items and advice which are commonly accepted and indisputable.

- <u>Keep the number of measures manageable</u> – Include measures when significant, but exclude measures that are merely interesting and not directly relevant.
- <u>Use a balance of measures</u> – Provide both output and outcome measures. Determine the critical areas of focus in your TMC and select measures for each area. Remember that some measures are more suited to a particular audience and ensure that the selection of measures can adequately convey understanding to each group of stakeholders.
- <u>Be flexible</u> – TMCs, especially new ones, should experiment with performance measures in order to find the right mix and set that capture and support the specific operating environment.
- <u>Go beyond the basics</u> – While it is recognized that simplicity and ease of measurement are attractive characteristics, especially to a new TMC, an agency should not shy away from areas that are hard to quantify or where data may be difficult to obtain. This pushes a TMC to grow and increase its capabilities and ultimately provide a better service to the stakeholders.
- <u>Establish regular reviews</u> – The performance measurement process should recognize the need for regular review. While the framework provides

iterative loops, a TMC must embrace this need. Regular reviews of performance measures can add, delete, or revise measures, identify additional data sources, refine the presentation of measures to stakeholders, and ensure a continued focus on operational goals.

PERFORMANCE MEASUREMENT PROCESS

In addition to the traits of good performance measures and the keys to a successful program, the process of performance measurement is critical to the overall success. Figure 8 highlights the performance measurement process. As has been stated previously, the choice of a specific measure follows from identifying both the goals and objectives of a particular program. In Figure 8, for incident management, the overall goal is to ensure timely response to incidents with a specific objective of reducing the incident detection time.

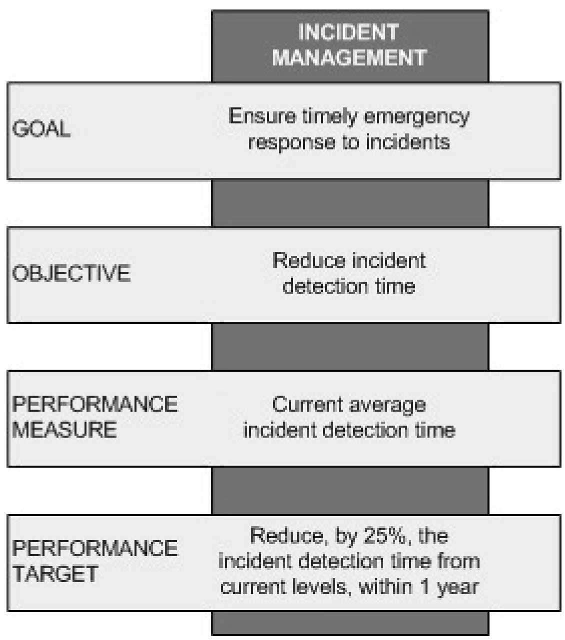

Figure 8. Typical Performance Measurement Process.

The measure itself then is the current incident detection time. It should be noted that by itself, the measure simply relates the current value of the incident detection time. It does not indicate if the goals and objectives are being met. For that assessment to be completed, the performance target must be known, which provides an identifiable mark with a time frame. These parameters can then be used to judge the effectiveness of the incident detection mechanism in an incident management program.

RECOMMENDED OPERATIONS PERFORMANCE MEASURES

The literature contains thousands of measures and dozens of lists to suggest performance measures to apply to particular situations. The sample listing below is intended to provide an awareness of the diversity of available measures. These measures have been stratified according to the goal classification system presented earlier. This list includes measures which are both outcome-based (examine satisfaction levels) and output-based (provide a quantitative assessment). It is also possible that measures may support more than one goal area and so may be listed twice.

- Accessibility
  - Average travel time
  - Average trip length
  - Model splits
- Mobility
  - 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
  - Annual hours of delay
  - Increase in system reliability
- Economic Development
  - Jobs supported
  - Jobs created
  - Economic cost of accidents
- Quality of Life
  - Perceived satisfaction with commute times
  - Perceived improvements in safety
  - Lost time due to congestion
  - Change in vehicle emissions
  - Accidents per vehicle miles traveled

- Ease of connections to inter-modal transfer points

- Environmental and Resource Conservation
  - Tons of pollutants emitted
  - Fuel consumption per vehicle miles traveled
  - Air quality rating
  - Modal splits
- Safety
  - Fatalities per vehicle mile traveled
  - Number of highway fatalities
  - Average duration of incidents
  - Average incident detection time
  - Average incident response time
  - Customer perception of system safety
- Operational Efficiency
  - Public expenditures on transportation system
  - Savings to taxpayers from incident management
  - Average travel cost per mile
  - Change in congested travel
  - Change in delay due to congestion
- System Condition and Performance
  - Lane miles of facilities under active management
  - Pavement serviceability rating
  - Volume to capacity ratios

HANDBOOK FOR DEVELOPING A TMC OPERATIONS MANUAL

The FHWA TMC Pooled Funds Study Program developed a technical reference manual that recommends practices for developing, maintaining, and using a TMC Operations Manual. Performance measurement is an integral component of this handbook. Suggested measures from the handbook include *(21)*:

- Trip character – average travel time, trip length, and modal splits;

- Mobility – vehicle miles of travel during congestion, travel time under congestion, delay per vehicle mile of travel or incidents, lost time due to congestion, annual hours of delay, and system reliability;
- Economic Development – jobs supported or created or the economic cost of accidents;
- Quality of Life – perceived satisfaction with commute times, perceived improvements in safety, lost time due to congestion, change in vehicle emissions, and accidents per vehicle miles traveled ease of connections to inter-modal transfer points;
- Environmental and Resource Conservation – tons of pollutants emitted, fuel consumption per vehicle miles traveled, air quality rating, and modal splits;
- Safety – fatalities per vehicle mile traveled, number of highway fatalities, average duration of incidents, average incident detection time, and average incident response time customer perception of system safety;
- Operational Efficiency – public expenditures on transportation system, savings to taxpayers from incident management, average travel cost per mile, change in congested travel, and change in delay due to congestion; and
- System Condition and Performance – lane miles of facilities under active management, pavement serviceability rating, and volume to capacity ratios.

GUIDE TO EFFECTIVE FREEWAY PERFORMANCE MEASURES

With so many performance measures to choose from, in addition to the incredible variety of applications where they can be used, it would be foolhardy for any reference or manual to identify a list of performance measures that ***must*** be implemented. Indeed, a comprehensive listing cannot be established by anyone other than the particular agency or TMC operating the system.

However, experience and research have provided significant direction on establishing a ***minimum*** set of performance measures that are ***recommended*** for implementation by a TMC. Identified in Table 11 (adopted from Table 4-5, Reference *(22)* these measures represent a suggested best practice for all of the characteristics that have been discussed, such as output vs. outcome, corridor vs. facility vs. regional, different goals, difference audiences, and more. Agencies should consider this list as a *starting point* and add or subtract measures, as appropriate to local needs and uses. For each measure listed in Table 11, the corresponding recommended geographic and time scales are identified. Additionally, the table is stratified into several common areas of performance measurement.

Table 11. Recommended Minimum Freeway Performance Measures.

Performance Measure	Geographic Scale	Time Scale
Congestion Focus Area		
Travel Time Index	Corridor, Areawide (minimum)	Peak hour, AM/PM peaks, Midday, Daily
Total Delay (vehicle-hours and person-hours)	Corridor, Areawide (minimum)	Peak hour, AM/PM peaks, Midday, Daily
Bottleneck ("Recurring") Delay (vehicle-hours)	Corridor, Areawide (minimum)	Peak hour, AM/PM peaks, Midday, Daily
Incident Delay (vehicle-hours)	Corridor, Areawide (minimum)	Peak hour, AM/PM peaks, Midday, Daily
Work Zone Delay (vehicle-hours)	Corridor, Areawide (minimum)	Peak hour, AM/PM peaks, Midday, Daily
Weather Delay (vehicle-hours)	Corridor, Areawide (minimum)	Peak hour, AM/PM peaks, Midday, Daily
Delay per Person	Corridor, Areawide	Peak hour, AM/PM peaks
Delay per Vehicle	Corridor, Areawide	Peak hour, AM/PM peaks
Percent of Vehicle Miles Traveled (VMT) with Average Speeds < 45 mph	Corridor, Areawide	Peak hour, AM/PM peaks
Percent of VMT with Average Speeds < 30 mph	Corridor, Areawide	Peak hour, AM/PM peaks
Percent of Day with Average Speeds < 45 mph	Corridor, Areawide	Daily
Percent of Day with Average Speeds < 30 mph	Corridor, Areawide	Daily
High Occupancy Vehicle HOV lane Volumes	Corridor, Areawide	AM/PM peaks
Reliability Focus Area		
Buffer Time Index	Corridor, Areawide	Peak hour, AM/PM peaks, Midday, Daily
95^{th} Percentile Travel Time Index	As needed	As needed
Incident Management Focus Area		
Detection Time	Corridor , Areawide	AM/PM peaks (minimum)
Verification Time	Corridor, Areawide	AM/PM peaks (minimum)
Response Time	Corridor, Areawide	AM/PM peaks (minimum)
Clearance Time	Corridor, Areawide	AM/PM peaks (minimum)
On-Scene Time	Corridor, Areawide	AM/PM peaks (minimum)
Total Duration	Corridor, Areawide	AM/PM peaks (minimum)
No. of Incidents by Type	Corridor, Areawide	AM/PM peaks (minimum)
Reporting by (Citizens, Police, Other Agencies) per month	Corridor, Areawide	AM/PM peaks (minimum)
Service Patrol Assists (total and by incident type)	Corridor, Areawide	AM/PM peaks (minimum)

Performance Measure	Geographic Scale	Time Scale
Work Zones Focus Area		
No. of Work Zones by Type of Activity	Corridor, Areawide	Daily
No. of Lane-Miles Lost	Corridor, Areawide	AM/PM peaks; midday, night
Lane-Mile-Hours of Work Zones	Corridor, Areawide	AM/PM peaks; midday; night
Average Work Zone Duration by Work Zone Type by Lanes Lost	Corridor, Areawide	Daily
Average Time Between Rehabilitation Activities	Areawide	N/A
Average Number of Days Projects Completed Late	Areawide	N/A
Ratio of Inactive Days to Active Days	Areawide	N/A
Weather Focus Area		
Hours Affected by (Rain, Snow, Ice, Surface Ice, High Winds, Fog, Dust, Smoke)	Corridor, Areawide	Daily
Lane-Miles Affected by (Rain, Snow, Ice, Surface Ice, High Winds, Fog, Dust, Smoke))	Corridor, Areawide	Daily
General Operations Focus Area		
Service Patrol Vehicles per Mile	Corridor, Areawide	Annually
Service Patrol Vehicles in Operation per Shift	Corridor, Areawide	Annually
Percent Freeway Miles with (Electronic Data Collection, Surveillance Cameras, Dynamic Message Signs [DMS], Service Patrol Coverage)	Areawide	Annually
Number of Messages Placed on DMSs	Corridor, Areawide	Annually
Individuals Receiving Traveler Information by Source (511, Other Direct Means)	Corridor, Areawide	Annually
Percent of Equipment (DMS, Surveillance Cameras, Sensors, Ramp Meters, Roadway Weather Information Systems (RWIS) in “Good” or Better Condition	Corridor, Areawide	Annually
Percent of Total Device-Days Out-of-Service (by Type of Device)	Corridor, Areawide	Annually
Number of Devices Exceeding Design Life	Corridor, Areawide	Annually
Mean Time Between Failure (MTBF) for Field Equipment (by Type of Device)	Corridor, Areawide	Annually

NATIONAL TRANSPORTATION OPERATIONS COALITION

In addition to the examples provided above, the National Transportation Operations Coalition (NTOC) with support from the Federal Highway Administration developed a list of national recommendations for performance measures. The goal of this list was to define approximately 10 measures commonly agreed upon by federal, state, and local transportation officials (NTOC). NTOC includes representatives from:

- America Association of State Highway and Transportation Officials (AASHTO),
- International City/County Management Association (ICMA),
- Transportation Research Board (TRB) ,
- Association of Metropolitan Planning Organizations (AMPO),
- American Public Works Association (APWA), and
- Institute of Transportation Engineers (ITE) *(23)*.

These national recommendations were developed to help local traffic administrators with the selection of performance measures and to encourage more national uniformity. The goal of these performance measures is to be used for internal management, external communications, and comparative measurements *(23)*.

The results from NTOC include the following suggestions of performance measures:

- customer satisfaction,
- extent of congestion – spatial,
- extent of congestion – temporal,
- incident duration,
- non-recurring delay,
- recurring delay,
- speed,
- throughput – person,
- throughput – vehicle,
- travel time – link,
- travel time – reliability, and
- travel time – trip.

Customer Satisfaction

Customer satisfaction is a qualitative measure based on the opinions of the motorist. Customer satisfaction includes operations on freeway, arterial, corridors, and regions. In most cases, customer satisfaction does not include surveys *(23)*. Some common questions to determine customer satisfaction include:

- How long was your commute to work?
- Are you satisfied with the amount of time required for local traffic activity?
- Did the TMC provide you with adequate information about the roadway?
- Are you satisfied with the various sources of information?

In most cases, the motorists' opinions are rated as very satisfied, somewhat satisfied, neutral, somewhat dissatisfied, very dissatisfied, and don't know or not applicable.

Extent of Congestion – Spatial

The extent of spatial congestion is defined by how widespread the congestion is. This performance is defined by the local agencies' definition of congestion. NTOC defines congestion as periods where travel time is 30 percent longer than unconstrained travel times. This performance measure is usually quantitative and may be defined as the number of centerline miles with congested conditions. This performance measure may also be defined on a regional or corridor level by the percentage of centerline miles that are under congestion versus the number of total miles in the region of the corridor. The calculation of this performance measure may also be defined by the time of day.

Extent of Congestion – Temporal

The temporal extent of congestion is the second performance measure that may be used to evaluate the congestion associated with a link, corridor, or region. This performance measure is quantitative and may be used in association with the spatial extent of congestion. The temporal performance measure is the time duration in which 20 percent of the roadway sections in the area of question are considered under congested by the spatial congestion definition.

Incident Duration

The incident duration is the amount of time elapsed from the notification of the incident until the incident has been removed or the service/response vehicles have left the incident. This measure is quantitative and may be defined as the amount of time elapsed between the notification of an incident and the amount of time for the complete clearing or removal of the incident. This measure may be applied to safety patrols, emergency response programs, and tow companies.

Non-Recurring Delay

Non-recurring delay is the number of vehicle hours that are associated with delays in excess of common recurring delays. Non-recurring delays may include holidays, the impacts of work zone construction periods, or intersections of two highway interchanges, etc.

Recurring Delay

Recurring delays are vehicle delays that are repeatable for the current time-of-day, day-of-week, and day-type. Congestion associated with recurring delay is defined by the travel time actually required to traverse the corridor and the unconstrained travel time. Common examples of recurring delay are morning and afternoon rush hours or the amount of time associated with a signal corridor.

Speed

The speed performance measure is the average point mean speed for vehicles traveling on an individual lane in one direction. The speed performance measure is typically used for various types of recurring and non-recurring congestion and unconstrained travel.

Throughput – Person

The throughput person performance measure is the number of people that travel across a segment of roadway over a given time. The typical unit for measurement is the number of persons per hour. This value includes vehicle occupants, pedestrians, and bicyclists. This performance measure is usually used to evaluate person-carrying capacity for planning and operations purposes.

Throughput – Vehicle

The throughput vehicle performance measure is the number of vehicles that travel across a segment of roadway for a particular time period. The throughput vehicle performance measure is in units of vehicles per hour. Similar to the previous performance measure, the vehicle throughput is calculated for recurring and non-recurring congestion as well as unconstrained flow.

Travel Time – Link

The travel time link performance measure is the amount of time required for one vehicle to travel in one single direction across a link. This performance measure includes vehicles on all roadway types that are traveling through recurring, non-recurring, and unconstrained flow. A link is typically a section of freeway between intersections or a segment between traffic signals or it may be defined by local agencies or municipalities. The units of measurement are the number of minutes per trip. The link-based travel time performance measure is used by planning and operations agencies *(23)*. Link-based travel time may be used for evaluating flow through work zones, improvements in single timing, or increased capacity along a roadway.

Travel Time – Reliability

Travel time reliability is the amount of additional time required by a motorist to reach the intended location within an allotted time over 95 percent of trips. Travel time reliability may be calculated for all types of roadways for all travel conditions. This measure is intended to be applied to a specific time of the day during which repeatable traffic and roadway conditions typically exist.

Travel Time – Trip

The travel time trip performance measurement is the average time required to travel from the origin to the destination and may be calculated for multiple modes of travel. This type of information is useful for traveler information and outreach. Examples might include the amount of time that it takes a motorist to travel through a work zone, travel to the airport, or travel the incoming/outgoing direction during a commuting period..

SUMMARY OF RECOMMENDED MEASURES

Despite the literature review and the sample listings above, there exists no definitive listing of recommended performance measures for the analysis of daily operations. As is evident, most of the measures in the literature focus on the higher levels of system analysis, such as system-wide or inter-agency operations. Throughout the second year of the project, the research team will be working to construct a recommended basic list that incorporates the principles of good performance measurement detailed above, as well as being specific enough to effectively analyze operations.

RECOMMENDED EMISSIONS PERFORMANCE MEASURES

EVALUATING THE PERFORMANCE OF AMBIENT AIR QUALITY

Natural phenomena and humans primarily cause air pollution. Reducing air pollution from natural sources is difficult, while reducing air pollution from human activities is relatively easier, especially in the transportation sector, which generates high levels of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x).

All air pollution, natural or human-made, can affect humans, animals, vegetation, materials, and structures, where the impact depends on the type of pollutant and exposure time. For example, an acute impact of coarse particulate matter (PM_{10}) concentration above 500 $\mu g/m^3$ can lead to human death within 24 hours, whereas the same effect may occur when ozone (O_3) concentration exceeds 1000 $\mu g/m^3$ for a one-hour exposure time. Some pollutants such as fine particulates ($PM_{2.5}$) also impact human health in the long term and lead to chronic disease *(24)*. Air pollution impacts can be divided into three levels: global, regional, and local. At the global level, carbon dioxide (CO_2) can increase global temperature, which leads to an increase in sea level and global warming. At the regional level, air pollution impacts can transfer from one region to another by wind. At the local level, the air pollution impacts occur in a particular area, such as county or city.

To assess any effects on ambient air quality, emissions' impact on humans, animals, vegetation, materials, and structures must be well understood. Thus, the first section presents the impacts of air pollution on human health, focusing on the six criteria air pollutants, carbon monoxide (CO), particulate matter (PM), nitrogen dioxide (NO_2), lead (Pb), sulfur dioxide (SO_2), and ozone (O_3) designated by the U.S. Environmental Protection Agency (EPA). The second section describes the National Ambient Air Quality Standards (NAAQS) and other countries' air pollution standards, as well as the application of air pollution indices. The third section addresses air pollution monitoring and measurement. Finally, the fourth section reviews the emission performance measures used in the United States and recommends performance measurement strategies to evaluate changes in emissions from the freeway system.

IMPACTS OF AIR POLLUTION ON HUMAN HEALTH

Carbon monoxide (CO)

Carbon monoxide is an odorless and colorless gas. According to the EPA *(25)*, the main contribution of carbon monoxide, approximately 60-95 percent, comes from automobiles through incomplete combustion processes, whereas other sources include both natural and industrial processes. Carbon monoxide occurs most significantly during cold weather. More incomplete combustion, which produces CO, occurs during cold temperatures; additionally, stable mixing conditions, which keep pollutants at ground level, occur more frequently during winter.

According to the EPA *(25)*, high risk of carbon monoxide impact will occur mostly to people who suffer cardiovascular disease, marginal or compromised cardiovascular and respiratory systems, and young infants and fetuses. Health impacts for carbon monoxide are shown in Table 12. The impacts of carbon monoxide vary by the percent of carboxyhemoglobin (COHb) in blood. When carboxyl hemoglobin levels in blood reach 3 percent, cardiovascular disease will be aggravated, while 80 percent COHb in blood can cause human death.

Table 12. Health Impacts Associated with Carboxyhemoglobin Blood Levels.

Percent of carboxy-hemoglobin (COHb) in blood	Human symptoms associated with this COHb level
80	• Death
60	• Loss of consciousness; death if exposure continues
40	• Collapse on exercise; confusion
30	• Headache, fatigue; judgment disturbed
20	• Cardiovascular damage; electrocardiographic abnormalities
5	• Decline (linear with increasing CoHb level) in maximal oxygen uptake of healthy young men undergoing strenuous exercise; decrements in visual perception, manual dexterity, and performance of complex sensorimotor tasks
4	• Decrements in vigilance (i.e., ability to detect small changes in one's environment that occur at unpredictable times); decreased exercise performance in both healthy persons and those with chronic obstructive pulmonary disease
3-6	• Aggravation of cardiovascular disease (i.e., decreased exercise capacity in patients with angina pectoris, intermittent claudication, or peripheral arteriosclerosis)

Source: *(26)*

According to Stern *(27)*, the effects of carbon monoxide depend on how much is accumulated in the human body. The level of carboxyl hemoglobin can increase with human exposure to high carbon monoxide levels, leading to a decrease in the capability of carrying oxygen from the lungs to body tissues. The amount of carbon monoxide in the human body can be estimated from the amount of carbon monoxide carried by hemoglobin. The relationship between the ratio of carbon monoxide and oxygen and the ratio of carboxyhemoglobin and oxyhemoglobin is described by the Haldane equation below:

$$\frac{\%COHb}{\%O_2Hb} = M\,\frac{(p_{CO})}{(p_{O_2})}$$

Where:

- M is known as the Haldane Constant and is approximately 245
- %COHb and $\%O_2Hb$ are the amount of hemoglobin combined with carbon monoxide and oxygen, respectively
- p_{CO} and p_{O_2} are the proportion of gas molecules of carbon monoxide and oxygen in air

The equation can describe the effects of high altitude (low p_{O_2}), carbon monoxide, and the removal of carbon monoxide from the human body by increasing the oxygen. However, the equation cannot estimate how much time the process will take, due to the individual differences in the capability of carrying oxygen to body tissues. In addition, humans can receive and excrete carbon monoxide from the body. Thus, the impacts of carbon monoxide on human health are complex and depend on exposure time, carbon monoxide concentration, and the amount of carbon monoxide remaining in the body after the processes of absorption and excretion.

Particulate Matter (PM)

According to Sattler *(28)*, particulate matter is any substance except pure water that exists in the atmosphere in the form of a liquid or solid. Particulates can be emitted directly from sources, such as vehicles or power plants, or formed via chemical reactions with other pollutants. Particulates are classified into two groups based on their dimensions: fine particles and coarse particles. Fine particles, or $PM_{2.5}$, have a diameter less than 2.5 micrometers. Sources of $PM_{2.5}$ include the combustion process in motor vehicles, power plants, and forest fires. Coarse particles, or PM_{10}, have a diameter greater than 2.5 micrometers but less than 10 micrometers. PM_{10} occurs through crushing or grinding operations or dust being stirred up by vehicles *(25)*.

The main sources of particulate matter are industrial processes. Table 13 shows that most particulates are generated from industrial processes, and only 20–21 percent of PM_{10} is generated by highway and off-highway vehicles. The particulates from different industries have diverse constituents, such as heavy metals and organic compounds. The impacts of particulate matter depend on the size of particulate. The smaller sizes of a particulate (diameter less than 0.5 micrometers) can be transported by wind over a longer distance than large size particulates. Thus, they will spread widely and have more serious effects than the larger particulates. According to Cooper and Alley *(29)*, small particle size causes more severe damage to human health than large particle size. $PM_{2.5}$ can penetrate deeply into lungs for longer periods of time, while PM_{10} can be trapped by nasal hairs or settle onto the mucous membranes in the nasal or oral passages or trachea. Insoluble particles can be swallowed or expectorated.

Pope et al. *(31)* studied the acute effects of particulates by increasing PM_{10} concentration in 10 $\mu g/m^3$ intervals. They evaluated data from 10 cities collected over one to a few days. Health measures including hospital admissions, respiratory and cardiac symptoms and deaths, and pulmonary function were studied. Factors such as age, gender, education, income, smoking, and health status were ignored due to the short period of time. The results of the study indicated that each increasing increment of 10 $\mu g/m^3$ PM_{10} concentration led to an increase of human disease of 1-3 percent, while damaging lung function by 0.1 percent (see Table 14).

Table 13. Nationwide Primary PM_{10} Emission Estimations from Mobile and Stationary Sources from 1985 to 1993.

Source Category	1985		1986		1987		1988		1989		1990		1991		1992		1993	
	1000x Short tons/ year	%PM	1000x Short tons/ year	%PM	1000x Short tons/ year	%PM	1000x Short tons/ year	%PM	1000x Short tons/ year	%PM	1000x Short tons/ year	%PM	1000x Short tons/ year	%PM	1000x Short tons/ year	%PM	1000x Short tons/ year	%PM
Fuel Combustion - Electric Utilities	284	9.6	289	9.8	282	9.7	278	9.4	278	9.6	291	10.0	253	8.9	255	9.3	270	10.1
Fuel Combustion - Industrial	234	7.9	231	7.8	226	7.8	230	7.8	229	7.9	228	7.8	229	8.0	223	8.2	219	8.2
Fuel Combustion - Other	896	30.3	902	30.6	910	31.5	918	31.2	922	31.7	930	32.0	942	33.1	819	30.0	723	27.2
Chemical and Allied Product Manufacturing	67	2.3	68	2.3	68	2.4	73	2.5	74	2.5	74	2.5	72	2.5	75	2.7	75	2.8
Metals Processing	147	5.0	137	4.6	131	4.5	141	4.8	142	4.9	140	4.8	136	4.8	137	5.0	141	5.3
Petroleum and Related Industries	32	1.1	31	1.1	30	1.0	29	1.0	28	1.0	28	1.0	28	1.0	27	1.0	26	1.0
Other Industrial Processes	317	10.7	321	10.9	314	10.9	314	10.7	308	10.6	306	10.5	300	10.5	303	11.1	311	11.7
Solvent Utilization	2	0.1	2	0.1	2	0.1	2	0.1	2	0.1	2	0.1	2	0.1	2	0.1	2	0.1
Storage and Transport	57	1.9	56	1.9	54	1.9	54	1.8	54	1.9	54	1.9	53	1.9	53	1.9	55	2.1
Waste Disposal and Recycling	279	9.4	275	9.3	265	9.2	259	8.8	251	8.6	242	8.3	245	8.6	246	9.0	248	9.3
Highway Vehicles	271	9.2	265	9.0	261	9.0	256	8.7	253	8.7	239	8.2	223	7.8	210	7.7	197	7.4
Off-Highway	368	12.5	372	12.6	350	12.1	387	13.2	372	12.8	372	12.8	367	12.9	379	13.9	395	14.8
Total	2953	100	2949	100	2893	100	2942	100	2909	100	2907	100	2849	100	2729	100	2661	100

Note: The sums of sub-categories may not equal total due to rounding (1 short ton = 9.08×10^5 grms).
Source: *(30)*

Table 14. Epidemiologic Associations of Increments of Daily Particulate Concentrations.

For each increment of 10 μg/m^3 PM_{10}	
Total mortality	Up 1%
Respiratory mortality	Up 3%
Hospital visits	
Respiratory	Up 1%
Asthmatics	Up 3%
Asthma attacks	Up 3%
Lung function	Down 0.1%

Source: *(31)*

According to the EPA *(25)*, a high risk of particulate impact occurs mostly to people who are sick with heart or lung disease, older adults, and children. People with lung disease may not be able to breathe as deeply. People with heart disease may experience chest pain or palpitations. Particulate pollution also can increase the risk of respiratory infections, such as asthma and chronic bronchitis. Health impacts of particulate matter are shown in Table 15. The impacts of particulates on human health vary by particulate size and exposure time.

The effects of particulates on human health should be lower at the present because $PM_{2.5}$ and PM_{10} levels are decreasing as technological advances have improved both automobile and industrial emission controls. According to the EPA *(25)*, average direct PM_{10} emissions decreased 13 percent nationally between 1992 and 2001, while direct $PM_{2.5}$ emissions decreased 10 percent nationally between 1992 and 2001.

Table 15. Health Impacts of Particulate Matter.

Concentration of particulate matter in air (μg/m^3)				Human symptoms and effects on visibility
Total suspended (TSP) > 25 (μm)	Thoracic TP > 10 (μm)	Fine FP > 2.5 (μm)	Exposure time	
2000	-	-	2 hr	• Personal discomfort
1000	-	-	10 min	• Direct respiratory mechanical changes
-	350	-	-	• Aggravation of bronchitis
180	90	-	-	• Increased respiratory disease symptoms
110	55	-	24 hr	• Increased respiratory disease risk

Sources: *(32, 33)*

Nitrogen dioxide (NO_2)

Although there are seven oxides of nitrogen that exist in the ambient air, only two of them, nitric oxide (NO) and nitrogen dioxide (NO_2), affect human health *(27)*.

Nitrogen dioxide comes from the thermal oxidation of N_2. NAAQS establishes nitrogen dioxide as one of the pollutants harmful to human health. However, the levels of nitrogen dioxide have been below the NAAQS for several years, so it poses little detriment to human health at present *(25)*. Health impacts of nitrogen dioxide are shown in Table 16. The impacts of nitrogen dioxide on human health, vegetation, materials, and visibility vary by the concentration of nitrogen dioxide in air measured in parts per million (ppm) and exposure time.

Table 16. Health Impacts of Nitrogen Dioxide.

Concentration of nitrogen dioxide in air (ppm)	Exposure time	Human symptoms and effects on vegetation, materials, and visibility
300	-	• Rapid death
150	-	• Death after 2 or 3 weeks by bronchiolitis fibrosa obliterans
50	-	• Reversible, nonfatal bronchiolitis
10	-	• Impairment of ability to detect odor of nitrogen dioxide
5	15 min	• Impairment of normal transport of gases between the blood and lungs in healthy adults
2.5	2 hr	• Increased airway resistance in healthy adults
2	4 hr	• Foliar injury to vegetation
1.0	15 min	• Increased airway resistance in bronchitics
1.0	48 hr	• Slight leaf spotting of pinto bean, endive, and cotton
0.3	-	• Brownish color of target 1 km distant
0.25	Growing season	• Decrease of growth and yield of tomatoes and oranges
0.2	8 hr	• Yellowing of white fabrics
0.12	-	• Odor perception threshold of nitrogen dioxide
0.1	12 weeks	• Fading of dyes on nylon
0.1	20 weeks	• Reduction in growth of Kentucky bluegrass
0.05	12 weeks	• Fading of dyes on cotton and rayon
0.03	-	• Brownish color of target 10 km distant
0.003	-	• Brownish color of target 100 km distant

Sources: *(34, 35)*

Lead (Pb)

According to Sattler *(28)*, lead comes from metals processing, such as ferrous and non-ferrous smelting and battery manufacturers or leaded gasoline. The major source of exposure to lead is food and water. Approximately 5–10 percent of ingested lead (0.12-0.35 mg/day) and 20–50 percent of inhaled lead can be metabolically absorbed in the body. A total of 60 micrograms of lead can be safely absorbed daily, whereas 120 micrograms daily is harmful. The effects of lead on human health include the damage of kidneys, liver, nervous system, and other organs. Moreover, excessive exposure may cause neurological impairment, such as seizures and mental retardation. The impacts are more severe on sensitive people, such as older people and children.

EPA issued standards in 1973 that called for a gradual phase-out of lead to reduce health risks from lead emissions due to gasoline, culminating in the Clean Air Act Amendments of 1990 and EPA regulations banning lead in motor vehicle gasoline. After 1995, impacts of lead were no longer a concern from transportation sources in United States.

Sulfur Dioxide (SO_2)

According to the EPA *(25)*, sulfur dioxide is a colorless, soluble, and reactive gas. Approximately 80 percent of sulfur dioxide comes from coal and fuel combustion in power plants and industrial processes. Sulfur dioxide can also convert to sulfuric acid, or H2SO4, in the atmosphere, with regional impacts (*24*). Approximately 30 percent of sulfur dioxide can form particulate matter by converting to sulfate aerosol (*26*). Sulfur dioxide that converts to sulfate can be transported by wind over long distances (hundreds of kilometers).

According to the EPA (*25*), people who suffer with asthma, cardiovascular disease, and chronic lung disease and children and older adults have the greatest risk of sulfur dioxide impacts. The symptoms of people who experience the health effects of sulfur dioxide are wheezing, chest tightness, and shortness of breath. More effects occur with higher sulfur dioxide levels, breathing rates, and exposure time. However, short-term effects are not permanent. Lung function can return to normal approximately one hour after exposure to sulfur dioxide ceases. Long-term exposure causes damage to the lung's defense mechanism and exacerbates existing heart disease. Impacts of SO_2 on human health and vegetation are shown in Table 17. The impacts of sulfur dioxide vary by concentration and exposure time.

Table 17. Human Health and Vegetation Impacts of Sulfur Dioxide.

Concentration of SO_2 in air (ppm)	Exposure Time	Human symptoms and effects on vegetation
400	-	• Lung edema; bronchial inflammation
20	-	• Eye irritation; coughing in healthy adults
15	1 hr	• Decreased mucociliary activity
10	10 min	• Bronchospasm
10	2 hr	• Visible foliar injury to vegetation in arid regions
8	-	• Throat irritation in healthy adults
5	10 min	• Increased airway resistance in healthy adults at rest
1	10 min	• Increased airway resistance in asthmatics at rest and in healthy adults at exercise
1	5 min	• Visible injury to sensitive vegetation in humid regions
0.5	10 min	• Increased airway resistance in asthmatics at exercise
0.5	-	• Odor threshold
0.5	1 hr	• Visible injury to sensitive vegetation in humid regions
0.2	3 hr	• Visible injury to sensitive vegetation in human regions
0.19	24 hr	• Aggravation of chronic respiratory disease in adults
0.07	Annual	• Aggravation of chronic respiratory disease in children

Sources: *(32, 36)*.

Ozone (O_3)

According to the EPA *(25)*, ozone is a gas composed of three oxygen atoms. Ozone occurs both in the stratosphere and troposphere. The effects of ozone on humans depend on the location. In the stratosphere layer, approximately 6–30 miles above ground level, ozone shields Earth from the sun's harmful ultraviolet rays that lead to skin cancer and cataracts. On the other hand, ozone in the troposphere layer, approximately 0–6 miles above the Earth's surface, is the main ingredient in photochemical smog. Cars, power plants, industrial boilers, refineries, chemical plants, and other sources generate ozone. However, the formation of ozone in the troposphere is complex—it needs the reaction of hydrocarbons with nitrogen oxides in the presence of sunlight. Ozone at the ground level is a harmful air pollutant and it causes eye, throat, and lung irritation. Moreover, it can aggravate asthma and other respiratory problems. The health impacts of ozone are shown in Table 18. The impacts of ozone vary by the concentration of ozone in air (ppm).

Table 18. Health Impacts of Ozone.

Concentration of ozone (ppm)	Human symptoms and vegetation injury threshold
10.0	• Severe pulmonary edema; possible acute bronchiolitis; decreased blood pressure; rapid weak pulse
1.0	• Coughing; extreme fatigue; lack of coordination; increased airway resistance; decreased forced expiratory volume
0.5	• Chest constriction; impaired carbon monoxide diffusion capacity; decrease in lung function without exercise
0.3	• Headache; chest discomfort sufficient to prevent completion of exercise; decrease in lung function in exercising subjects
0.25	• Increase in incidence and severity of asthma attacks; moderate eye irritation. For sensitive individuals, reduction in pulmonary lung function; chest discomfort; irritation of the respiratory tract, coughing and wheezing
0.15	• Threshold for injury to vegetation

Sources: *(37, 38)*

AIR QUALITY STANDARDS AND THEIR APPLICATION

The U.S. Clean Air Act provides two kinds of air quality standards: primary standards and secondary standards. Primary standards are set to protect public health, while secondary standards protect public welfare. Last amended in 1990, the U.S. Clean Air Act requires EPA to set NAAQS. EPA established NAAQS for six pollutants: sulfur dioxide (SO_2), particulate matter (PM_{10} and $PM_{2.5}$), carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2), and lead (Pb), as shown in Table 19.

Table 19. U.S. Federal Primary and Secondary NAAQS.

Pollutant	Type of standard	Averaging time	Frequency parameter	Concentration	
				µg/m^3	ppm
SO_2	Primary	24 hour	Annual Maximum[(1)]	365	0.14
		1 year	Arithmetic mean	80	0.03
	Secondary	3 hr	Annual maximum[(1)]	1300	0.5
$PM_{2.5}$	Primary	24 hr	Annual maximum[(2)]	65	-
		1 year	Arithmetic mean[(3)]	15	-
	Secondary	24 hr	Annual maximum	-	-
		1 year	Arithmetic mean[(3)]	15	-
PM_{10}	Primary	24 hr	Annual maximum[(1)]	150	-
		1 year	Arithmetic mean[(4)]	50	-
	Secondary	24 hr	Annual maximum	150	-
		1 year	Arithmetic mean[(4)]	50	-
CO	Primary	1 hr	Annual maximum[(1)]	40,000	35.0
		8 hr	Annual maximum[(1)]	10,000	9.0
O_3	Primary and secondary	8 hr	Arithmetic mean[(5)]	-	0.08
NO_2	Primary and secondary	1 year	Arithmetic mean	100	0.053
Pb	Primary and secondary	3 months	Arithmetic mean	1.5	-

(1) Not to be exceeded more than once per year.
(2) To attain this standard, the 3-yr average of the 98th percentile of 24-hr concentrations at each population-oriented monitor within and area must not exceed 65 µg/m3.
(3) To attain this standard, the 3-yr average of the weighted annual mean PM_{10} concentration at each monitoring with an area must not exceed 50 µg/m^3
(4) To attain this standard, the 3-yr average of the weighted annual mean $PM_{2.5}$ concentration from single or multiple community-oriented monitors must not exceed 15.0 µg/m^3.
(5) To attain this standard, the 3-yr average of the fourth-highest daily maximum 8-hr average ozone-concentrations measured at each monitor within an area over each year must not exceed 0.08 ppm.
Sources: *(24, 39)*

Also, there are standards for "prevention of significant deterioration" (PSD) in specified areas. The standards in those areas will be set lower than either the primary or secondary standards (see Table 20).

In the United States, the EPA designates areas attainment or non-attainment. An attainment area is an area that meets the national primary or secondary ambient air quality standard; a non-attainment area is an area that does not meet the national primary or secondary ambient air quality standard in Table 19. In Texas, four areas are classified as non-attainment for ozone: San Antonio, Dallas-Fort Worth, Houston-Galveston-Brazoria, and Beaumont-Port Arthur. EPA classifications for ozone non-attainment areas range from marginal to extreme (see Table 21).

Table 20. Federal PSD Concentration Increments.

Pollutant	Increment[a] (μg/m^3)
Class I areas[b]	
Particulate matter	
• TSP, annual geometric mean	5
• TSP, 24-hr maximum	10
Sulfur dioxide	
• Annual arithmetic mean	2
• 24-hr maximum	5
• 3-hr maximum	25
Nitrogen dioxide	
• Annual arithmetic mean	2.5
Class II areas[c]	
Particulate matter	
• TSP, annual geometric mean	19
• TSP, 24-hr maximum	37
Sulfur dioxide	
• Annual arithmetic mean	20
• 24-hr maximum	91
• 3-hr maximum	512
Nitrogen dioxide	
• Annual arithmetic mean	25
Class III areas[d]	
Particulate matter	
• TSP, annual geometric mean	37
• TSP, 24-hr maximum	75
Sulfur dioxide	
• Annual arithmetic mean	40
• 24-hour maximum	182
• 3-hr maximum	700
Nitrogen dioxide	
• Annual arithmetic mean	50

(a) Increments over base air quality
(b) Class I areas are pristine, e.g., national parks, national seashores, natural wilderness areas.
(c) Class II areas where moderate deterioration is allowed (unless otherwise designated, all areas are Class II).
(d) Class III areas are specifically designated as heavy industrial.
Source: *(24)*

Table 21. Air Quality Classifications for Ozone.

Level of Air Quality	Concentration (ppm)
Extreme	0.280 ppm or above and has 20 years to attain.
Severe 17	0.190–0.280 ppm and has 17 years to attain.
Severe 15	0.180–0.190 ppm and has 15 years to attain.
Serious	0.160–0.180 ppm and has nine years to attain.
Moderate	0.138–0.160 ppm and has six years to attain.
Marginal	0.121–0.138 ppm and has three years to attain.

Source: *(40)*

Houston-Galveston-Brazoria (Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller counties) and Dallas-Fort Worth (Collin, Dallas, Denton, Tarrant, Ellis, Johnson, Kaufman, Parker, and Rockwall counties) are currently "moderate non-attainment" areas and have until June 15, 2010, to reach attainment. Beaumont-Port Arthur (Hardin, Jefferson, and Orange counties) and San Antonio (Bexar, Comal, and Guadalupe counties) are currently "marginal non-attainment and basic (deferred)" areas, respectively. San Antonio and Beaumont-Port Arthur must reach attainment by December 31, 2007, and June 15, 2007, respectively.

APPLICATION OF AIR POLLUTION STANDARDS

Air Pollution Index

The Pollutant Standards Index (PSI), later known as Air Quality Index (AQI), was established by the EPA and the President's Council on Environmental Quality in 1976. It is used by state and local agencies as the uniform index for indicating quality of ambient air to the public health based on NAAQS and the significant harm level (SHL).

The AQI includes sub-indices for various pollutants such as O_3, PM, CO, SO_2, and NO_2. The AQI uses colors to represent the impacts of each pollutant on human health. It is utilized to present the air quality in a particular area based on a scale from 0 through 500 (see Table 22).

Table 22. AQI Values and Air Quality Descriptor.

AQI Values	Levels of Health Concern	Colors
0 to 50	Good	Green
51 to 100	Moderate	Yellow
101 to 150	Unhealthy for Sensitive Groups	Orange
151 to 200	Unhealthy	Red
201 to 300	Very Unhealthy	Purple
301 to 500	Hazardous	Maroon

According to the EPA, each color reflects a different level of human health impacts, as described below:

- “Good” – An AQI value between 0 and 50 represents satisfactory air quality, and air pollution poses little or no risk.
- “Moderate” – An AQI value between 51 and 100 represents acceptable conditions; however, some pollutants may present a moderate health concern for a very small number of people. For example, people who are unusually sensitive to ozone may experience respiratory symptoms.
- “Unhealthy for Sensitive Groups” – AQI values between 101 and 150 may affect some sensitive groups of people, such as people with lung or heart disease, children, and elderly people.
- “Unhealthy” – Everyone may begin to experience health effects when AQI values are between 151 and 200. Members of sensitive groups may experience more serious health effects.
- “Very Unhealthy” – AQI values between 201 and 300 trigger a health alert, meaning everyone may experience more serious health effects.
- “Hazardous” – AQI values over 300 trigger health warnings of emergency conditions. The entire population is more likely to be affected.

When the pollutant has an index value above 100, ozone will affect more sensitive people including children and people with asthma. $PM_{2.5}$ will affect people with respiratory or heart disease, the elderly, and children. PM_{10} will affect people with respiratory disease. CO will affect people with heart disease. SO_2 will affect people with asthma. Index values between 200 and 400 are defined as alert, warning, and emergency levels. An index value of 500 indicates severe related impacts including death.

Recently, the EPA has been developing new and innovative programs in order to provide more information for the public through the Ozone Mapping Project and community action programs. The program can provide real-time AQI reporting to the public. Ozone mapping is used in 31 states including 1500 monitors across the eastern and central United States and California.

AQI Procedure

a) Identify the highest concentration pollutants.

b) Use Table 23 to find the two breakpoints that contain the concentration. If the concentration is larger than the highest breakpoint in Table 23, then use the last two breakpoints in Table 23. If concentration is equal to a breakpoint, then it is equal to the index value. If the concentration is between two breakpoints, then calculate the index using equation below:

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{HI} - BP_{Lo}}\left(C_p - BP_{Lo}\right) + I_{Lo}$$

Where:

I_p = the index value for $pollutant_p$
C_p = the truncated concentration of $pollutant_p$
BP_{Hi} = the breakpoint that is greater than or equal to C_p
I_{Hi} = the AQI value corresponding to BP_{Hi}
I_{Io}= the AQI value corresponding to BP_{Lo}

c) Round the index to the nearest integer.

d) The breakpoint sub-indices for various pollutant concentrations are shown in Table 23. The EPA describes the impacts of four pollutants; ozone, particulates, carbon monoxide, and sulfur dioxide, in Table 24 through Table 27.

Table 23. Proposed Breakpoints for O_3, $PM_{2.5}$, PM_{10}, CO, and SO_2 Sub-Indices.

AQI Value	O_3		PM		CO, 8-hr (ppm)	SO_2, 24-hr (ppm)	NO_2, 24-hr (ppm)
	8-hr (ppm)	1-hr [1] (ppm)	PM_{25}, 24-hr (µg/m^3)	PM_{10}, 24-hr (µg/m^3)			
0-50	0.000-0.064	-	0.0-15.4	0-54	0.0-4.4	0.000-0.034	(2)
51-100	0.065-0.084	-	15.5-40.4	55-154	4.5-9.4	0.035-0.144	(2)
101-150	0.085-0.104	0.125-0.164	40.5-65.4	155-254	9.5-12.4	0.145-0.224	(2)
151-200	0.105-0.124	0.165-0.204	65.5-150.4	255-354	12.5-15.4	0.225-0.304	(2)
201-300	0.125-0.374	0.205-0.404	150.5-250.4	355-424	15.5-30.4	0.305-0.604	0.65-1.24
301-400	(3)	0.405-0.504	250.5-350.4	425-504	30.5-40.4	0.605-0.804	1.25-1.64
401-500	(3)	0.505-.604	350.5-500.4	505-604	40.5-50.4	0.805-1.004	1.65-2.04

(1) Areas are generally required to report the AQI based on 8-hr ozone values. However, there are a small number of areas where an AQI based on 1-hr ozone values would be more precautionary. In these cases, in addition to calculating the 8-hr ozone index value, the 1-hr ozone index value may be calculated and the maximum of the two values is reported.

(2) NO2 has no short-term NAAQS and can generate an AQI only above a value of 200.

(3) When 8-hr O3 concentrations exceed 0.374 ppm, AQI values of 301 or higher must be calculated with 1-hr O3 concentrations.

Source: *(40)*

Table 24. Air Quality Index (AQI): Ozone.

Index Values	Levels of Health Concern	Cautionary Statements
0-50	Good	None
51-100*	Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion outdoors.
101-150	Unhealthy for Sensitive Groups	Active children and adults, and people with lung disease, such as asthma, should reduce prolonged or heavy exertion outdoors.
151-200	Unhealthy	Active children and adults, and people with lung disease, such as asthma, should avoid prolonged or heavy exertion outdoors. Everyone else, especially children, should reduce prolonged or heavy exertion outdoors.
201-300	Very Unhealthy	Active children and adults, and people with lung disease, such as asthma, should avoid all outdoor exertion. Everyone else, especially children, should avoid prolonged or heavy exertion outdoors.
301-500	Hazardous	Everyone should avoid all physical activity outdoors.

* Generally, an AQI of 100 for ozone corresponds to an ozone level of 0.08 ppm (averaged over 8 hr).

Table 25. Air Quality Index (AQI): Particle Pollution.

Index Values	Levels of Health Concern	Cautionary Statements
0-50	Good	None
51-100*	Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion.
101-150	Unhealthy for Sensitive Groups	People with heart or lung disease, older adults, and children should reduce prolonged or heavy exertion.
151-200	Unhealthy	People with heart or lung disease, older adults, and children should avoid prolonged or heavy exertion. Everyone else should reduce prolonged or heavy exertion.
201-300	Very Unhealthy	People with heart or lung disease, older adults, and children should avoid all physical activity outdoors. Everyone else should avoid prolonged or heavy exertion.
301-500	Hazardous	People with heart or lung disease, older adults, and children should remain indoors and keep activity levels low. Everyone else should avoid all physical activity outdoors.

*An AQI of 100 for particles up to 2.5 micrometers in diameter corresponds to a level of 40 micrograms per cubic meter (averaged over 24 hr). An AQI of 100 for particles up to 10 micrometers in diameter corresponds to a level of 150 micrograms per cubic meter (averaged over 24 hr).

Table 26. Air Quality Index (AQI): Carbon Monoxide (CO).

Index Values	Levels of Health Concern	Cautionary Statements
0-50	Good	None
51-100*	Moderate	None
101-150	Unhealthy for Sensitive Groups	People with heart disease, such as angina, should reduce heavy exertion and avoid sources of CO, such as heavy traffic.
151-200	Unhealthy	People with heart disease, such as angina, should reduce moderate exertion and avoid sources of CO, such as heavy traffic.
201-300	Very Unhealthy	People with heart disease, such as angina, should avoid exertion and sources of CO, such as heavy traffic.
301-500	Hazardous	People with heart disease, such as angina, should avoid exertion and sources of CO, such as heavy traffic. Everyone else should reduce heavy exertion.

* An AQI of 100 for carbon monoxide corresponds to a CO level of 9 ppm (averaged over 8 hr).

Table 27. Air Quality Index (AQI): Sulfur Dioxide (SO_2).

Index Values	Levels of Health Concern	Cautionary Statements
0-50	Good	None
51-100*	Moderate	None
101-150	Unhealthy for Sensitive Groups	People with asthma should consider reducing exertion outdoors.
151-200	Unhealthy	Children, asthmatics, and people with heart or lung disease should reduce exertion outdoors.
201-300	Very Unhealthy	Children, asthmatics, and people with heart or lung disease should avoid outdoor exertion. Everyone else should reduce exertion outdoors.
301-500	Hazardous	Children, asthmatics, and people with heart or lung disease should remain indoors. Everyone else should avoid exertion outdoors.

* An AQI of 100 for sulfur dioxide corresponds to an SO_2 level of 0.14 ppm (averaged over 24 hr).

Stewart *(41)* discusses some weak points of AQI. First, the air pollution indices do not cover the number of people exposed to given levels of air pollution. Second, they cannot evaluate the effects of the change in transportation improvements or natural variations, such as dust storms or the amount of rain. Third, they do not include interactions among the different pollutants. Finally, all the indices are created based on a linear ratio assumption between ambient levels and given standards. However, many cases show the relationships are non-linear.

Air Quality Health Index (AQHI)

The Air Quality Health Index, or "AQHI" also represents the ambient air quality. AQI is established by the EPA and used in the United Sates, while AQHI is established by the United Kingdom Department of Environment and used in European countries. The differences between AQHI and AQI are (1) AQI scale ranges from 0 to 500 (see Table 22), while AQHI uses 1-10 (see Table 28); (2) air quality represented by AQI is based on the one pollutant with the highest value, while AQHI is based on the sum of those health risks from each of the pollutants in the index. The pollutants considered in AQHI include ozone, particulates, nitrogen dioxide, sulfur dioxide, and carbon monoxide. The health impacts associated with different levels on the scale are shown in Table 28.

Table 28. Human Health Impacts Based on AQHI Scales.

Banding	Index	Health Descriptor
Low	1	Effects are unlikely to be noticed even by individuals who know they are sensitive to air pollutants.
	2	
	3	
Moderate	4	Mild effects, unlikely to require action, may be noticed amongst sensitive individuals.
	5	
	6	
High	7	Significant effects may be noticed by sensitive individuals and action to avoid or reduce these effects may be needed (e.g., reducing exposure by spending less time in polluted areas outdoors). Asthmatics will find that their 'reliever' inhaler is likely to reverse the effects on the lung.
	8	
	9	
Very High	10	The effects on sensitive individuals described for 'High' levels of pollution may worsen.

Source: *(42)*

In daily life, people are exposed to multiple pollutants. Thus, the AQHI based on the sum of health risks from each of the pollutants index should provide better information about health impacts, by using relative weights of different pollutants in various periods of time, compared with AQI. However, since the United States uses the AQI, and the public and regulatory personnel in the United States are already familiar with the AQI, it will be recommended for use by TxDOT.

AIR POLLUTION MONITORING AND MEASUREMENT

Air pollution is an important problem that affects human health and welfare. Ambient concentrations of pollutants (mass/volume) in real time can be measured directly through stationary monitoring networks; mobile source emissions can be measured or modeled.

Ambient Concentration Monitoring

Stationary monitoring is used to monitor ambient concentrations over an extended time period. On the other hand, it may be used to measure pollutants before and after infrastructure is constructed or some operational changes. Data obtained from stationary monitoring include the concentration of various air pollutants and weather conditions, such as temperature, wind speed, and wind direction.

According to the EPA, monitoring stations in the United States are utilized for many purposes. The network of monitoring stations is used to assess the air quality at local, regional, and national levels; assess the heath impacts, effectiveness of control programs, and source impacts; help form the basis for new control programs; and provide information to the public. The EPA's ambient air quality monitoring program establishes four categories of monitoring stations:

- Photochemical Assessment Monitoring Stations (PAMS) – measure ozone precursors (volatile organic compounds [VOCs] and nitrogen oxides [NOx], which react to form ozone);
- State and Local Air Monitoring Stations (SLAMS) – obtain air pollution information in strategic locations across the nation;
- National Air Monitoring Stations (NAMS) – a part of the SLAMS network added in order to obtain more detailed information; and
- Special Purpose Monitoring Stations (SPMS) – measure air pollution for short-term monitoring.

The pollutants being measured through monitoring sites are carbon monoxide, ozone, nitrogen oxides, PM_{10}, lead, sulfur dioxide, and, in some cases VOCs. Table 29 describes national monitoring networks, including sampling frequency. Several networks in addition to PAMS, SLAMS, and NAMS are also described.

Table 29. Summary Table of National Ambient Air Monitoring Networks.

Network	Approximate Current Number of Sites	Historical High # Sites	Sampling Reporting Freq.	Notes
SLAMS/ NAMS				
Ozone	1167	1167 (2002)	Hourly (May -September)	
$PM_{2.5}$	1200	1200 (2002)	24-hr average; mix of daily, every third day, and every sixth day	
PM_{10}	1214	1763 (1991)	Mix of 24-hr avg., every sixth day; and hourly	
SO_2	592	3158 (1975)	Hourly	
NO_2	437	1944 (1975)	Hourly	
CO	498	648 (1981)	Hourly	
Pb	247	1393 (1981)	24-hr avg., every sixth day	
TSP	215	4894 (1981)	24-hr avg., every sixth day	
PM2.5				
Federal Reference Method (FRM) mass	(1100)			
Continuous mass	200		Hourly	
Speciation	54 trends; 160 SIP, 140 IMPROVE		Mostly 24-hr avg; every third day	Major ions (sulfate, nitrate, ammonium); carbon fractions (organic and elemental); trace metals
PAMS	77 sites in 25 Metropolitan Statistical Areas (MSAs)		Mix of hourly, 3-hr avg. and 24-hr average (56 VOCs, total nonmethane organic carbon (TNMOC) and carbonyls throughout ozone season)	Ozone and NO_2 include SLAMS/NAMS
Toxics	280 (10 National pilot sites)		Broad range of metals, VOCs, semivolatile organic compounds (SVOCs); metals, VOCs, aldehydes; 18 species 24-hr avg., every sixth or twelfth day	
CASTNET	70		Total nitrate, sulfate, ammonium 2-week avg. samples collected continuously	Ozone and IMPROVE measurements included above

Source: *(43)*

State environmental agencies, local Air Pollution Control Districts (APCDs), cities, private contractors, and the National Parks Service (NPS) are responsible for operating NAMS, PAMS, SLAMS, and SPMS. Data from the monitoring sites may include (based on purposes of data collection):

- The concentration of ozone, CO, NO_2, SO_2, $PM_{2.5}$, PM_{10}, VOCs, lead; light scatter monitored with nephelometer; nonmethane hydrocarbons (total) collected in continuous monitors, nonmethane hydrocarbons (speciated) collected in canisters (3-hour or 24-hour samples); and total hydrocarbons monitored by continuous analyzer
- Meteorological data
  - dew point temperature
  - barometric pressure
  - relative humidity
  - total solar radiation
  - ambient air temperature
  - ultraviolet radiation
  - vertical wind speed
  - wind direction
  - wind speed

Sampling or analysis methods may include:

- atomic absorption spectroscopy – graphite oven from high-volume sampler;
- chemiluminescence;
- colormetric;
- conductimetric;
- emission spectrometry ICAP (inductively coupled argon plasma);
- fluorescence;
- flame photometric;
- gas chromatography;
- inductively coupled plasma-mass spectrometer;
- nondispersive infrared;

- low-volume single-channel sampler, size selective inlet;
- high-volume sampler, size-selective inlet;
- low-volume sequential sampler, size-selective inlet;
- ultraviolet absorption; and
- X-ray fluorescence.

The sampling or analysis method is based on type of pollutants collected (see Table 30).

Table 30. Methods for Pollutant Measurement.

Pollutants	Concentration Measurement
Ozone	• Ultraviolet absorption
CO	• Nondispersive infrared
NO_2	• Chemiluminescence
SO_2	• Fluorescence
$PM_{2.5}$	• Low-volume sequential sampler, size-selective inlet • Low-volume single channel sampler, size-selective inlet
PM_{10}	• High-volume sampler, size-selective inlet
Lead	• Atomic absorption – Graphite oven from high-volume sampler • X-ray fluorescence

According to Evens *(44)*, sampling site selection should be based on the purpose of the collected data. In addition, the site selected should be able to provide additional data to define the chemical and meteorological conditions in that site area. Evans *(44)* advises the monitoring site scales in Table 31; the factors affecting site selection include climatological data (wind and frequency), topography and population data, emission inventory data, dispersion modeling, security from vandalism, absence of nearby structures, and cost and availability of land and electric power. Table 32 describes monitoring site criteria from the Texas Commission on Environmental Quality (formerly the Texas Natural Resource Conservation Commission). Additional monitoring sites can be selected using the criteria in Table 31 and Table 32. For example, micro and middle scale (local level) sites that are located within 500 m should be appropriate for capturing the air pollution impacts in a particular area, such as ramps or intersections for on-road emissions.

Table 31. Monitoring Site Scales.

Siting Scales	Distance	Monitoring Objectives
Micro, Middle, Neighborhood, (sometimes urban)	1 - 100 m 100 m – 0.5 km 0.5 - 4.0 km	Highest concentration affecting people
Neighborhood Urban	0.5 - 4.0 km 4 - 50 km	High-density population exposure
Micro Middle Neighborhood	1 - 100 m 100 m – 0.5 km 0.5 - 4.0 km	Source impact
Neighborhood Region	0.5 - 4.0 km 10 - 100 km	General/background concentration

Source: *(45)*

Table 32. Monitoring Site Criteria.

Level	Description
Microscale	Defines the concentrations in air volumes associated with area dimensions ranging from several meters up to about 100 meters
Middle scale	Defines the concentrations typical of areas up to several city blocks in size with dimensions ranging from about 100 meters to 0.5 kilometer.
Neighborhood scale	Defines the concentrations within some extended area of the city that has relatively uniform land use with dimensions in the 0.5 to 4.0 kilometers range.
Urban Scale	Defines the overall, citywide conditions with dimensions on the order of 4 to 50 kilometers. This scale would usually require more than one site for definition.

Source: *(45)*

Mobile Monitoring

Remote Sensing

Remote sensing is a method to measure on-road emissions in real time. Remote sensing device systems (RSDs) use a radiation absorption principle to measure CO, CO_2, HC, or NO_x. Infrared is used for measuring CO, CO_2, and HC, whereas ultraviolet is utilized for measuring NO_x since NO_x absorption characteristics are stronger and more selective in the ultraviolet light spectrum.

Source and detector units are positioned on opposite sides of the roadway. The system operates by projecting infrared (IR) or ultraviolet (UV) radiation continuously across a roadway. The detectors receive the radiation signal through the air. With no vehicle passing the IR or UV line, the signal is strong. The signal weakens when vehicles pass through the radiation stream. The amount of IR or UV light absorbed is related to pollutants. RSDs with a freeze-frame video camera that can detect the license plate of vehicles can store emissions information for each monitored vehicle, based on the license plate number.

The uses of RSDs depend on the study purpose. RSDs should be an appropriate emission measurement tool to capture the real-time emissions at a particular location, such as ramps or intersections. However, it may be not an effective way to measure the emission for the entire roadway, especially on freeways that have many lanes.

On-Board Emission Measurement

Another approach to measure on-road emissions is on-board emission measurement. Unlike the snapshot measurements of RSDs, which can capture the emissions only at a particular location, on-board emission measurement uses a "micro-scale" approach to capture the on-road emissions in real time at any point of time and location where the vehicle is driven. Real-time emissions can be measured for various driving patterns (accelerations and decelerations), roadway geometry (grade and roadway condition), driver behavior, etc. In addition, on-board emission measurement using a micro-scale approach should be an effective method to evaluate the impacts of signal improvements at intersections, which are too small to observe in a macroscopic model. Also, the on-board emission measurement that can measure the real-time emission data for actual driving conditions should prove advantageous over micro-scale modeling. However, when continuous data are needed at a particular location, on-board emission measurement may not be an effective method, especially for studying the trends of emissions due to season and incident events *(46)*.

Macroscopic Emission Models

The macroscopic modeling component consists of a model that has been developed for freeway and arterial road networks for the whole region. Macroscopic emission models, such as MOBILE6 (currently used in many states in United States) and the California Air Resources Board's (CARB) EMission FACtor (EMFAC) software model (currently used in California) are commonly used to estimate the on-road emissions in the United States. These models can predict gram per mile emissions of HC, CO, NO_x, CO_2, PM, and toxics from cars, trucks, and motorcycles under various conditions. MOBILE6 and EMFAC estimated composite emission rates are a function of vehicle type and age, average speed, temperature, altitude, vehicle load, air conditioning usage, and vehicle operating model. These models calculate region-wide emission factors (EFs) in grams/mile for arterials, freeways, ramps, and other minor road connectors. The emission rates can be combined with vehicle activities (VMT, number of trips, and vehicle-hours traveled) from a travel demand model to develop highway emission inventories expressed in tons per time period *(46)*.

Microscopic Emission Models

Microscopic emission models are utilized to simulate traffic, such as freeway segments, freeway on-ramps, intersections, etc. Second by second vehicle characteristics, traffic conditions, and roadway conditions are required in order to obtain the emission rates. Due to the ability to estimate the emissions second by second, microscopic emission models are capable of assessing the impact of signal re-timing, modeling roadway sections, etc. CORSIM is one of the microscopic emission models commonly used to estimate on-road emissions. CORSIM applies emission rates from dynamometer testing, summarized in speed and acceleration look-up tables, to estimate total roadway emissions. Microscopic models are more accurate than region-wide macroscopic models for evaluating micro-scale impacts, such as those of signal coordination, but may still be inaccurate if not calibrated for local conditions. Also, vehicle operating history can impact emissions, but speed-acceleration tables cannot account for this. Microscopic models, however, represent the best strategy for estimating benefits prior to implementing a micro-scale traffic improvement project *(46)*.

EMISSION PERFORMANCE MEASURES

A good emission performance measure should be practical and realistic. It should be easy for all people to understand and easy to develop with available data. Moreover, it should be provided in time, so users, such as travelers or the government, still have time to react to the air pollution condition. For example, an emission performance measure such as AQI can provide air quality information along the roadway network so that travelers will know the air quality condition and try to avoid routes with high air pollutants. In addition, the DOTs can use emission performance measures to evaluate project implementation and future funding allocations.

Since the initial realization that air pollution is a significant problem in parts of the United. States, emission performance measures such as AQI and PSI, have been used to assess the ambient air quality in many states and regions. Although the use of indicators has been increasing, the definition and selection of emission performance measures are still at an early stage. There are no exact rules for performance measure selection. Criteria for choosing measures can be identified by the people who collect and use the data or experts who understand the strength and limitation of each performance measure. However, good performance measures should be a direct consequence of activities. For example, emissions generated from roadways are defined as an outcome measure. If the desired result is minimizing emissions, the emission rate should be a good performance measure (direct consequence). A proxy measure may sometimes be used in the absence of suitable performance measures due to time, budget constraints, or unavailability of data. For example, when considering the desired result of emission reductions, instead of using the direct outcome measure of emission rate, output measures, such as the vehicle registration or congestion level, may serve as indirect performance measures. Unfortunately, a proxy measure may not present a good result or measure because the correlation may be weak. Consistency and data availability sometimes limit the effectiveness of the performance measures.

Table 33 lists the typical emissions performance measures compiled from the literature. In addition, the table identifies if the measure is qualitative or quantitative in nature, as well as identifying the data needs for the calculation of the measure. Table 34 reduces this list to those measures which are appropriate for use in the transportation arena. Table 34 also identifies whether the measure can be used in real time.

Table 33. Emissions Performance Measures.

Outcome Emission Measures	Target	Qualitative Quantitative	Data Needs	Note
On Road Emissions Ambient concentration (ppm) Emission Rate (ppm/mile)	Maintain the ambient concentration less than the NAAQS	Quantitative	1-min, 5-min, 1-hr, 24-hr data for tactical level (depending on each pollutant)	Applicable for transportation
# of non-attainment areas	Lowering each year the percentage of non-attainment and maintenance areas in a state	Quantitative	Annual Data	Applicable for transportation
# and % of residents exposed to air that meets NAAQS for SO_2, PM_{25}, CO, O_3, NO_2, and Pb	Reducing of # of deaths, hospitalizations, asthma attacks, and lost school and work day in the state	Quantitative	Annual Data	Not applicable for transportation. Due to the meteorological conditions, emissions disperse everywhere; it is difficult to capture the exact # of residents exposed to air that meets NAAQS
Subarea Air Quality Index using on-road mobile sources during peak (concentration/sq. kilometer grid cells; highest grid cell, median grid cell, etc.)	Maintain the air quality index less than 100	Quantitative	1-min, 5-min, 1-hr, 24-hr data	Applicable for transportation
Air Quality Index (AQI)	Maintain the air quality index less than 100	Quantitative	1-hr data for AQI reporting	Applicable for transportation
Number of days exceeding air quality standard annually	Reducing the percentage of days exceeding the air quality standard in each year	Quantitative	Annual Data	Applicable for transportation
Tracking changes in ozone concentrations based on the 3-year average of the annual fourth highest daily maximum 8-hr concentration. (8-hr NAAQS for ozone)	Decrease the 3-year average ozone concentration	Quantitative	Annual Data	Applicable for transportation
# of deaths, hospitalizations, asthma attacks and lost school and work days in the state	Reduce the # of deaths, hospitalizations, asthma attacks, and lost school and work day in the state	Quantitative	Annual Data	Not applicable for transportation. Factors unrelated to air pollution (epidemics, incidences of smoking, etc.) can impact number of deaths, hospitalizations, and other measures. Separating the impacts of air quality requires extensive statistical analysis.

Table 33. Emissions Performance Measures (cont).

Outcome Emission Measures	Target	Qualitative Quantitative	Data Needs	Note
Percent of fuel consumption of cleaner fuels	Improving each year the percentage of cleaner fuels	Quantitative	Annual Data	Applicable for transportation
Pounds of pollutants emitted from roadways	Reducing the pounds of pollutants emitted each year	Quantitative	Annual Data	Applicable for transportation
Avg. fuel economy for TXDOT fleet Maintenance vehicle Non-maintenance vehicle	Improving each year the percentage of avg. fuel economy for TXDOT fleet	Quantitative	Annual Data	Applicable for transportation
Percentage of passenger car fleet classified as high fuel economy	Improving each year the Percentage of passenger car fleet classified as high fuel economy	Quantitative	Annual Data	Applicable for transportation
VMT of all vehicles	Reducing each year the VMT of all vehicle	Quantitative	Annual Data	Applicable for transportation
VMT of commercial vehicles in non-attainment areas	Reducing each year the VMT of commercial vehicles in non-attainment areas	Quantitative	Annual Data	Applicable for transportation
# of incidents on roadways	Reducing each year the # of incidents and accidents on roadways	Quantitative	Annual Data	Applicable for transportation
Vehicle occupancy rate	Improving each year the rate of vehicle occupancy	Quantitative	Annual Data	Applicable for transportation
Pounds of transportation emissions per number of vehicles (modeled)	Reducing each year pounds of transportation emissions per number of vehicles (modeled)	Quantitative	Annual Data	Applicable for transportation
Pounds of transportation emissions per VMT (modeled)	Reducing each year pounds of transportation emissions per VMT (modeled)	Quantitative	Annual Data	Applicable for transportation

Table 34. Emissions Performance Measures Applicable to Transportation.

Outcome Emission Measures	Spatial Variation	Temporal Variation	Type of outcome measure	Transportation Impact	Data Applicable in Real Time
Air Quality Index (AQI)	Regional	Less than one year	Direct outcome measure	Contributing	Applicable
Number of days exceeding air quality standard annually	Regional	1 to 25 years	Direct outcome measure	Contributing	Not Applicable
Tracking changes in ozone concentrations based on the 3-year average of the 4th highest daily maximum 8-hour concentration	Regional	1 to 25 years	Direct outcome measure	Contributing	Not Applicable
Percent of fuel consumption defined as cleaner fuels	Regional	1 to 25 years	Proxy outcome measure	Direct	Not Applicable
On road emission – ambient concentration (parts per million)	Corridor / Local / Sub-Regional	<1 year	Direct outcome measure	Direct	Applicable
On-road emission-emissions rate (parts per million per mile)	Corridor / Local / Sub-Regional	<1 year	Direct outcome measure	Direct	Applicable
Number of non-attainment areas	Statewide	1 to 25 years	Direct outcome measure	Contributing	Not Applicable
Subarea Air Quality Index	Corridor / Local	<1 year	Direct outcome measure	Direct	Applicable
Vehicle Occupancy Rate	Regional	1 to 25 years	Proxy outcome measure	Direct	Not Applicable
Pounds of transportation emissions per number of vehicles	Regional	1 to 25 years	Proxy outcome measure	Contributing	Not Applicable
Pounds of transportation emissions per vehicle miles traveled (VMT)	Statewide	1 to 25 years	Proxy outcome measure	Contributing	Not Applicable

Table 34 lists only the appropriate outcome measures applicable to transportation based on temporal-spatial variation for each level of planning. Considering the criteria for choosing measures, direct outcome measures (occurrence, condition, or consequence of activities comes from transportation process related to air quality) should assess the quality of ambient air better than the proxy or contributing outcome measures.

Table 35 lists the outcome measures appropriate to transportation and considers their performance with respect to the following evaluation criteria: measurability, data applicable in real time, clarity, and directness. Scoring is as follows:

- Measurability – can it be measured (quantified)?
  - 1 = Yes
  - 0 = No
- Data applicable in real time – can data be collected directly in the field in real time?
  - 1 = Yes
  - 0 = No
- Clarity – will it be understandable for most TxDOT TMC personnel?
  - 1 = Yes
  - 0 = No
- Directness – Is it a direct measure of transportation impacts on air quality?
  - 1 = Yes
  - 0 = No

Table 35 provides the summary scores for the evaluation, with larger numbers representing those measures that are most suited for transportation applications. Ambient concentration, emission rate, and subarea air quality index are the best outcome measures to assess the quality of air, with the highest scores. These measures work best at the tactical or localized level. At the strategic or regional level, AQI represents the best outcome measure with the highest score (3). The other outcome measures may be used to assess air quality as supplementary measures.

Table 35. Evaluation of Emission Performance Measures Applicable to Transportation.

Outcome Emission Measure	Measurability	Data Applicable In Real Time	Clarity	Directness	Total
On road emission - Ambient concentration (ppm) - Emission rate (ppm/mile)	☑	☑	☑	☑	4
Number of non-attainment areas	☑		☑		2
Subarea Air Quality Index	☑	☑	☑	☑	4
Air Quality Index (AQI)	☑	☑	☑		3
Number of days exceeding air quality standard annually	☑		☑		2
Tracking changes in ozone concentrations based on the 3-year average of the annual fourth highest daily maximum 8-hour concentration.	☑				1
Percent of fuel consumption defined as cleaner fuels	☑		☑		2
Average fuel economy for TXDOT fleet - Maintenance veh. - Non-maintenance veh.	☑		☑		2
Percentage of passenger car fleet classified as high fuel economy	☑		☑		2
VMT of all vehicles	☑		☑		2
VMT of commercial vehicles in non-attainment areas	☑		☑		2
Number of incidents and accidents on roadway	☑		☑		2
Vehicle occupancy rate	☑		☑		2
Pounds of transportation emissions per number of vehicles (modeled)	☑		☑		2
Pounds of transportation emissions per VMT (modeled)	☑		☑		2

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