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Decision Matrix and Guidance Document for Proactive Congestion Management

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For:

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16. Abstract

This project developed a decision matrix that transportation agencies can use to determine the viability of proactive congestion management strategies that meet their overall objective of mitigating congestion. This decision matrix can be used to help an operating agency identify possible operational strategies to mitigate or delay the onset of the congestion and can provide infrastructure owner/operators with a selection matrix based on operational conditions and available field data by which they can select potential operational strategies to consider for implementation. The matrix was augmented with data from the University of South Florida research team in "Proactive Congestion Management" and complements the simulation models of strategies developed by the University of South Florida. The matrix is also the foundation of an online screening tool that provides high-level guidance and recommendations on specific congestion management strategies that might support proactive congestion management.

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List of Abbreviations

AADT	average annual daily traffic
AI	artificial intelligence
ATCT	adaptive signal control technology
ATM	active traffic management
ATE	average absolute travel time error
AVI	automatic vehicle identification
BER	block error rate
BSM	basic safety message
CA	capacity adequacy
CACC	cooperative adaptive cruise control
CAM	cooperative awareness message
CAV	connected automated vehicle
CV	connected vehicle
DSS	decision support system
I2V	infrastructure-to-vehicle
IOO	infrastructure owner/operator
FHWA	Federal Highway Administration
FM	Farm-to-Market
FRBS	fuzzy rule-based system
GHG	greenhouse gas
GMM	Gaussian Mixture Model
GPS	global positioning system
GSM	global system for mobility communications
HOT	high occupancy/toll vehicle
HOV	high occupancy vehicle
IEEE	Institute of Electrical and Electronics Engineers
IH	Interstate Highway
ISM	industrial scientific medical band
KL	Kullback–Leibler
LJT	link journey time
LoRaWAN	long range wide-area network
LOS	level of service
LPWAN	low-power wide area network
MVDS	microwave vehicle detection system
NB-IoT	narrow band internet of things IoT
NPRMDS	National Performance Measures Research dataset
NRC	non-recurrent congestion
OBU	onboard unit
RFID	radio-frequency identification
RPART	recursive partitioning and regression decision tree
RSU	roadside unit
RTT	round-trip delay Time
SEM	standard error of mean
SH	State Highway

SNR	signal-to-noise ratio
SUTRAC	Scalable Urban Traffic Control
TEB	travel time error bias
TSMO	transportation systems management and operations
TTI	Texas A&M Transportation Institute
VSM	variable message sign
USDOT	United States Department of Transportation
USF	University of South Florida
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything

Executive Summary

Traffic congestion occurs frequently with the increase of traffic demand. The reasons why congestion occurs are varied, including weekday peak hour, unpredictable weather, crashes, special events, etc. Some traditional technologies have been applied to predict the occurrence of congestion, but new technologies can be used as they emerge and become mainstream to forecast and minimize the effects of recurrent and non-recurrent congestion having on delay and disruption. The overall research objective of the Proactive Congestion Management project was to determine appropriate methods for combining datasets from conventional sources and innovative sources to carry out strategies that impend congestion. The advances in big-data science lead the results of easing congestion to success.

The objective of this study was to develop a decision matrix which can be used to determine the viability of proactive congestion management strategies that meet the overall objective of mitigating congestion. Incorporating results from the University of South Florida (USF) research team, the decision matrix can be used to help an operating agency identify possible operational strategies to mitigate or delay the onset of the congestion and could provide infrastructure owner/operators with a selection matrix based on operational conditions and available field data by which they can select potential operational strategies to consider for implementation. The matrix and related decision tool complement the simulation models of strategies developed by the University of South Florida and provides specific guidance and recommendations that could benefit agencies in the rapid deployment of strategies in response to potential field condition triggers.

Under the collaboration efforts associated with this project, the TTI Team assembled and provided comprehensive data sets from readily available sources to the University of South Florida (USF) to augment the data they collected for their modeling, simulation, and analysis. After initial data gathering and discussions between key members of the TTI and USF project team, the TTI Team prepared two comprehensive sets of data from two different locations in Texas: the first four roadway segments of which are in Harris County and the other of which is in Bell County. Data provided included the number of lanes in the segment, the segment length, posted speed limit, average annual daily traffic (AADT), and the percent heavy vehicles in the traffic stream.

The TTI team prepared a comprehensive review of literature related to congestion management and data. The review provided insight into the challenges of managing congestion and how data access and usability can enhance the overall approach to managing the network. The review focused on network congestion, including recurrent and non-recurrent congestion, and data and congestion management, including Bluetooth, wi-fi, and probe data, basic safety messages and connected vehicles, radar data, and data fusion.

The TTI research team assessed different proactive congestion management strategies that have the potential to either delay the onset or mitigate the impact of recurring and nonrecurring congestion on roadway safety and operations. As part of that assessment, the team focused on strategies that can assist in improving an existing congestion management process (CMP) by correlating the planning goals and objectives of the CMP to the proactive management strategies that can help attain those objectives. Many of the strategies selected fit within the broad range of strategies under ATM. Those included in the matrix include:

- Value Priced Express Toll Lanes;
- Express Toll Lanes Non-Value Priced;
- HOV Lanes;
- Truck Restricted Lanes;

- Non-tolled Express Lanes;
- HOT Lanes;
- Exclusive Transitways;
- Exclusive or Dedicated Truck Lanes;
- Multifaceted Managed Lanes;
- Dynamic Speed Limits;
- Part-Time Shoulder Use;
- Queue Warning;
- Adaptive Ramp Metering;
- Dynamic Merge Control;
- Dynamic Truck Restrictions;
- Dynamic Rerouting and Traveler Information;
- Automated Enforcement;
- Dynamic Lane Reversal. and
- Dynamic Lane Use Control.

While this list is not exhaustive in terms of all TSMO strategies that can improve congestion, they have the potential to be utilized in a proactive manner and can incorporate real-time, near real-time, and CAV-related data to enhance their effectiveness.

The TTI research team developed a decision matrix based on goals, objectives, constraints, and other operational conditions and preferences for use by infrastructure owner operators with which they can select potential operational strategies to consider for implementation to work toward proactive congestion management. The matrix is intended to complement the simulation models of strategies developed by University of South Florida and to provide specific guidance and recommendations that will benefit agencies in the rapid deployment of strategies in response to potential field condition triggers. The TTI team coordinated with the USF research team to incorporate data elements that emerged from their simulation models that could be used in the proactive selection of strategies to help mitigate congestion.

The TTI team developed a draft matrix structure based on an active management screening tool (AMST) that was developed previously. The purpose of the AMST was to help agencies better assess the potential of active management strategies for their region. It was structured to provide beneficial information and guidance related to active management strategies. It was also intended to directly link the transportation planning process with operations by providing regions with information on which operational strategies they might include in the regional transportation plan that have the potential to provide the most benefit to the regional transportation network. Given the similarities between the original AMST and the overall intent of the proactive congestion management matrix, the TTI team used the original structure of the AMST as a launching point to optimize resources. The project team expanded the proactive congestion management strategies included in the new matrix to match those noted previously and developed content around the following critical elements:

- active management goals;
- active management objectives;
- active management performance measures;
- implementation constraints;
- enabling infrastructure and technologies;

- cost considerations (core elements, operations, maintenance)
- application geography;
- compatible strategies; and
- potential benefits.

The TTI Team then refined the structure of the Proactive Congestion Management Strategy Framework (PCMSF) around these elements to ensure the relationships between the proactive congestion management strategies and the elements were accurately and fully represented.

The TTI team converted the proactive congestion management decision matrix into an online screening tool that offers users an easy approach to selecting potential operational strategies based on their preferred or anticipated active management objectives. The tool was developed using an online decision tree platform and is currently housed online at the following URL: https://zingtree.com/show/203440350000. Initially, the user selects a preferred active management objective from a list of options. Once a user selects an objective, the user then selects an active management operational strategy for possible deployment. Upon strategy selection, the tool generates a detailed output that includes the critical information included in the matrix. The tool is easy to restart or revise to select various options. The user can print the results and make comparisons as desired to determine what strategies might be viable for their jurisdiction.

The TTI team prepared and delivered a webinar targeted at infrastructure owner-operators to introduce the decision matrix and demonstrate its use for operational strategy decision-making using the online screening tool. The TTI team has prepared documentation for the research project and plans to develop research articles for delivery to target audiences via conferences and peer-reviewed journals. The final version of the online screening tool and related matrix will be made available online for ready access by practitioners. Social media outreach will also be developed to ensure the broad dissemination of the research results.

It is the hope of the authors that by providing transportation agencies with a readily available and easy-to-use tool and matrix to screen for proactive congestion management operational strategies can have a positive impact on transportation networks where these strategies are feasible. Potential transportation improvements can include an increase in average throughput for congested periods, an increase in overall capacity, a decrease in primary accidents, a decrease in secondary accidents, a decrease in accident severity, an overall harmonization of speeds during congested periods, an increase in trip reliability, and the ability to delay the onset of freeway breakdown. Proactive congestion management has the potential to help transportation agencies address the ever-increasing challenge of doing more with less and operating existing facilities in the most efficient manner possible.

Introduction

For decades, the United States has grappled with the challenge of providing convenient and safe transportation options to system users in a rapidly evolving landscape. Over the years, transportation professionals have worked to optimize the significant investment of the transportation network to ensure it is safer, more efficient, and sustainable (Kuhn 2019). This trend toward optimizing the system has coalesced around the concept of transportation systems management and operations (TSMO). Specifically, TSMO consists of strategies implemented by infrastructure owner/operators (IOOs) which target operational improvements to help maintain or improve system performance in lieu of adding capacity (FHWA 2022).

The goal of TSMO is to get the most performance out of the transportation facilities already in place. This requires knowledge, skills, and techniques to administer comprehensive solutions that can be quickly implemented at relatively low cost. This may enable transportation agencies to "stretch" their funding to benefit more areas and customers. TSMO also helps agencies balance supply and demand and provide flexible solutions to match changing conditions. Key benefits of TSMO can include, but are not limited to:

- Improved safety;
- Smoother and more reliable traffic flow;
- Reduced congestion;
- Less wasted fuel;
- Cleaner air;
- Improved quality of life;
- Increased economic vitality; and
- More efficient use of resources (facilities, funding).

TSMO is a systematic approach to address mobility, reliability, and safety issues by capitalizing on the existing infrastructure investment through optimization. It centers on the guiding principles of active, integrated, and performance-driven management and operations. Key descriptors associated with TSMO include dynamic, predictive, proactive, performance driven, continuous monitoring, and supply and demand-oriented in nature. (Kuhn 2019). The overall objective of TSMO is for an agency to extract as much capacity and operational efficiency as possible out of its existing network and to optimize its investment in mobility while improving safety. TSMO establishes the foundation for long-term system management of the transportation system, which represents a different way of doing business on the part of operating agencies. Efficient management and operations can benefit all users of a network and possibly delay the need to expand capacity, particularly when resources to do so are limited.

Proactive Congestion Management

The foundation of proactive congestion management is the active management cycle. As illustrated in Figure 1, transportation agencies can utilize a four-step cycle to actively and dynamically managing their networks. These steps are as follows:

- Monitor systems;
- Assess system performance;
- Evaluate and recommend dynamic actions; and
- Implement dynamic actions. (FHWA 2012).

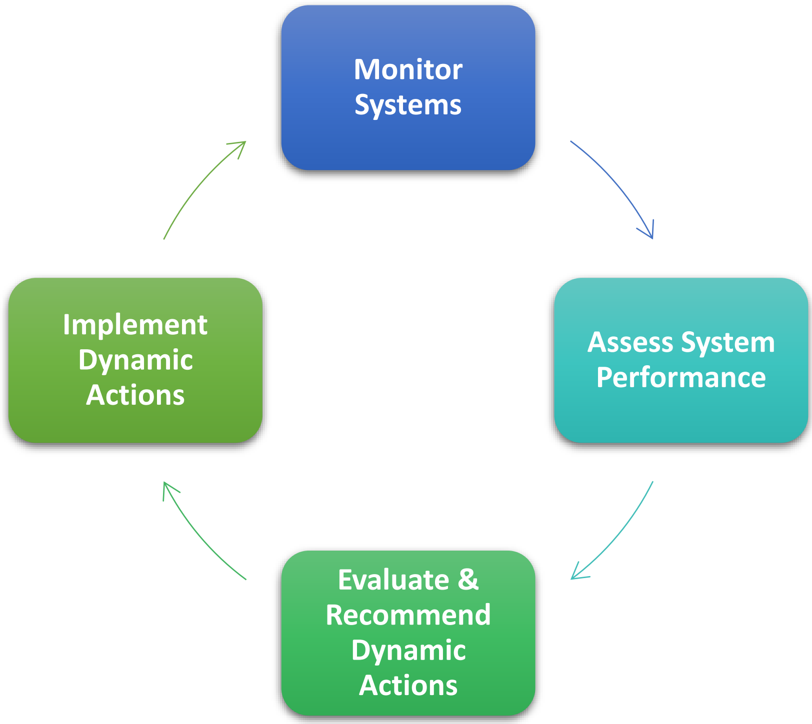

Figure 1. The active management cycle. (Adapted from FHWA 2012).

Throughout the active management cycle of TSMO, IOOs monitor their systems and networks and assess their performance against a broad range of measures and benchmarks. Agency personnel then evaluate the ongoing performance of the system and recommend dynamic actions to modify operations to enhance and improve system performance. Upon implementation of the selected actions, an agency continues monitoring the system to determine if the actions affected the desired improvement on performance. TSMO differs from traditional roadway network management in that the actions address immediate and near-term needs in system operations rather than longer-term expansion.

As agencies advance capabilities, the specific cycle step of evaluating and recommending dynamic actions begins to move TSMO from reactive and takes along a proactive path. As illustrated in Figure 2, the active management continuum evolves and becomes more advanced as technologies, capabilities, and congestion evolve. Using modeling and predictive analysis techniques, an agency can begin to identify the need for and deploy TSMO strategies prior to the onset of congestion and to dynamically manage and adapt those strategies based on changing conditions. Taking the proactive approach to congestion management works to delay on onset of congestion, reduce the duration of congestion, or potentially eliminate breakdown altogether. Efficient management and operations can benefit all users of a network and possibly delay the need to expand capacity, particularly when resources to do so are limited.

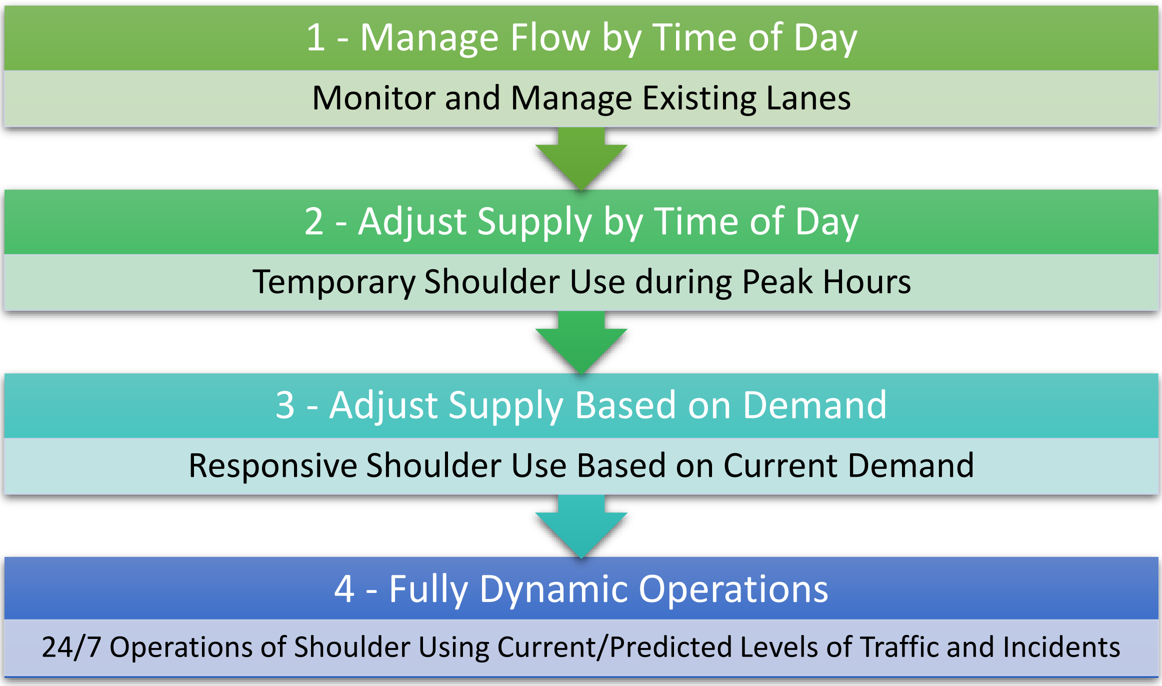

Figure 2. Active management continuum (Adapted from FHWA 2012).

Research Objective

Traffic congestion occurs frequently with the increase of traffic demand. The reasons why congestion occurs are varied, including weekday peak hour, unpredictable weather, crashes, special events, etc. Some traditional technologies have been applied to predict the occurrence of congestion, but new technologies can be used as they emerge and become mainstream to forecast and minimize the effects of recurrent and non-recurrent congestion having on delay and disruption. The overall research objective of the Proactive Congestion Management project was to determine appropriate methods for combining datasets from conventional sources and innovative sources to carry out strategies that impend congestion. The advances in big-data science lead the results of easing congestion to success.

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The following sections provide a detailed account of the research conducted by the Texas A&M Transportation Institute (TTI) Team as part of this study. The sections include the following:

- Data Identification, Preparation, and Delivery;
- Literature Review;
- Identification of Proactive Management Strategies;
- Development of the Decision Matrix;
- Dissemination of Research Results; and
- Final Remarks.

Data Identification, Preparation, & Delivery

Under the collaboration efforts associated with this project, the TTI Team assembled and provided comprehensive data sets from readily available sources to the University of South Florida (USF) to augment the data they collected for their modeling, simulation, and analysis. After initial data gathering and discussions between key members of the TTI and USF project team, the TTI Team prepared two comprehensive sets of data from two different locations in Texas. The first four roadway segments listed in Table 1, for which the TTI Team provided data, are in Harris County. The approximate locations of these segments are illustrated in Figure 3. The fifth roadway segment listed in Table 1 is located in Bell County and is shown in Figure 4. Table 1 provides additional details related to these locations, including the number of lanes in the segment, the segment length, posted speed limit, average annual daily traffic (AADT), and the percent heavy vehicles in the traffic stream.

Table 1. Geometric properties of the matched segments in Texas.

Map Number	Location	County	Zip Code	Number of Lanes	Length (miles)	Speed Limit (mph)	AADT (vehicles)	% Heavy vehicles
1	North Sam Houston Tollway: Wilson Rd to W Lake Houston Parkway	Harris	77049	3	2.0	65	80,000	10%
2	SH-99: Cinco Ranch Blvd to Kingsland	Harris	77494	2	2.0	70	95,000	5%
3	SH-288: FM 58 (Croix Rd) to FM 101 (Bailey Ave)	Harris	77578	2	1.4	65	70,000	20%
4	SH-288: FM 101 (Bailey Ave) to FM 518 (Broadway St)	Harris	77578	2	1.9	65	70,000	20%
5	IH-35: Prairie Dell to FM 2115	Bell	76571	3	1.4	75	80,000	25%

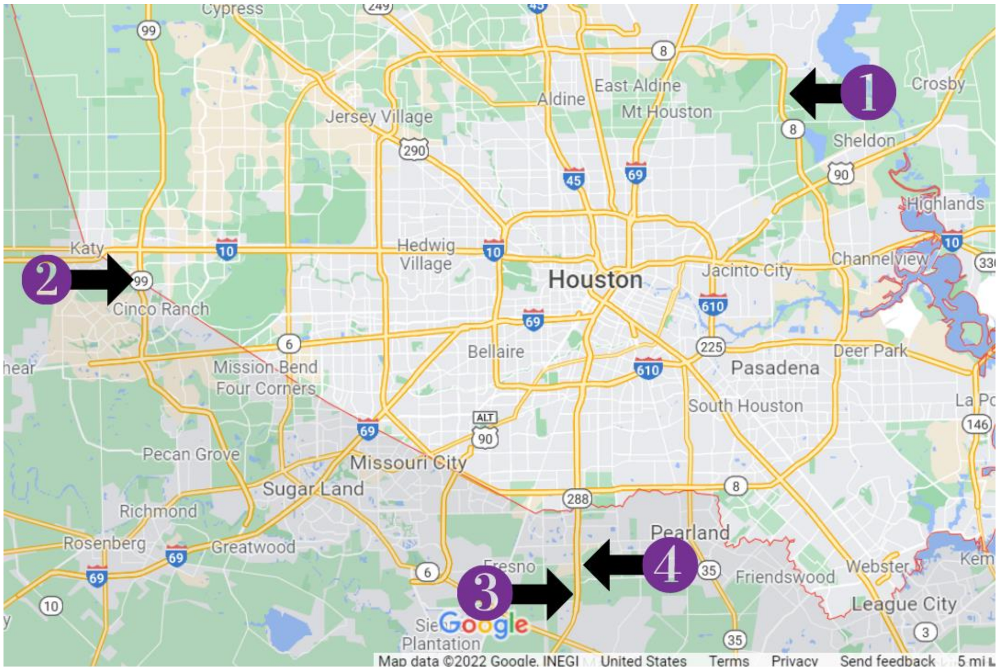


Figure 3. Location of data sources, Harris County, Texas. (Adapted from Google 2022).

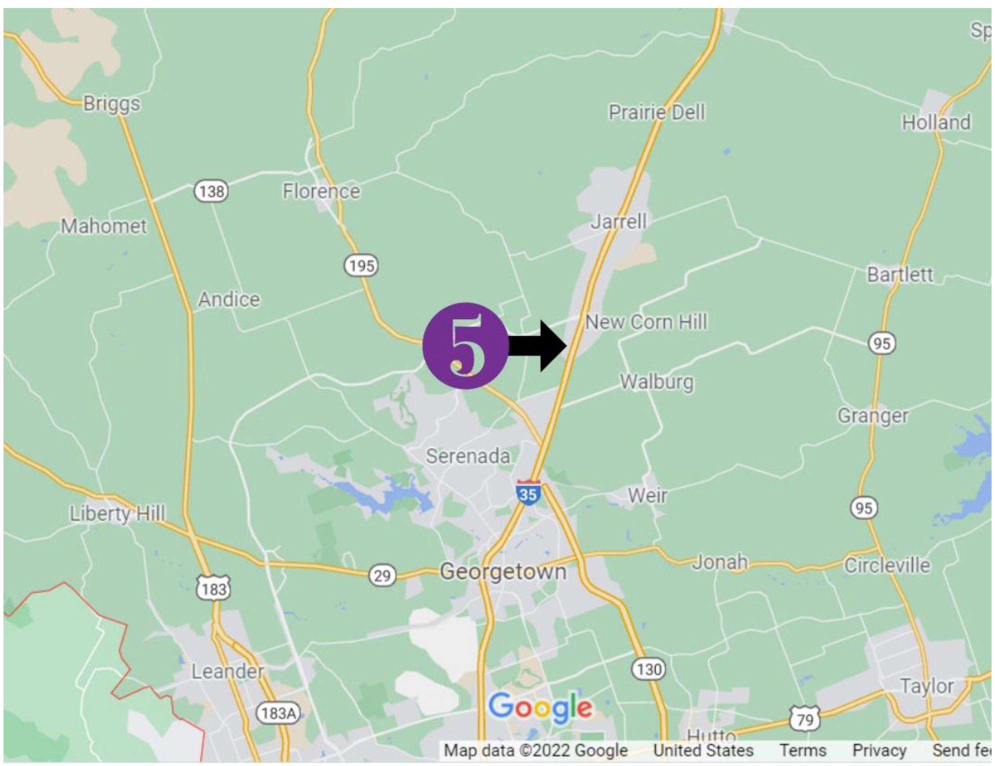


Figure 4. Location of data source, Bell County, Texas. (Adapted from Google 2022).

These roadway segments were selected after analysis by the USF team to determine their compatibility with the Florida roadway segments and data. The specific data assembled by the TTI Team were acquired through cooperative agreements with the Texas Department of Transportation via Houston TranStar, I-35 work zone and other relevant sources. The datasets contain information related to lane section, including Bluetooth travel times, volume, roadway geometrics, lane closure information, and incident information. The lane sections used for further simulation research by USF included 2 and 3 lanes per direction as noted previously. The following list shows the detailed information included in datasets.

- 5-minute radar data aggregations from a single sensor (spot speeds and volumes). Each record contains the following elements:
    - Aggregation start time;
    - Sensor ID;
    - Sensor direction;
    - Total volume;
    - Average speed;
    - Average lane occupancy;
    - Number of lanes in sample;
    - Number of samples;
- 5-minute travel time aggregations from the Bluetooth data (element names included in files);
- Incident records (element names included in files);
- Planned lane closure records (element names included in files); and
- KML of sensor locations.

Additional information related to the use of this data in the USF research is included in a separate report prepared by the USF Team.

Literature Review

The following represents a comprehensive review of literature related to congestion management and data. This review provides insight into the challenges of managing congestion and how data access and usability can enhance the overall approach to managing the network.

Network Congestion

Congestion management and forecasting has been at the forefront of transportation agencies for decades. (Lomax et al., 1997) defined congestion as the following:

- Congestion is travel time or delay more than the normally incurred under light or free-flow travel conditions; and
- Unacceptable congestion is travel time or delay more than an agreed-upon norm. The agreed-upon norm may vary by type of transportation facility, travel mode, geographic location, and time of day.

Two other concepts frequently used in determining congestion include:

- <u>Mobility</u> – the ability of people and goods to move quickly, easily, and cheaply to where they are destined as a speed that represents free-flow or comparably high-quality conditions; and
- <u>Accessibility</u> – the achievement of travel objectives within time limits regarded as acceptable (Lomax et al., 1997).

As populations increase and roadway capacities "shrink", agencies face the challenge to quickly and accurately identify problems and implement mitigation strategies. Historically, transportation professionals have measured traffic congestion using identifiers such as speed, travel time, delays, level of service (LOS), and congestion indices. These performance measure are shown in Figure 5 (Afrin & Yodo 2020). Table 2 also presents a comparison of the congestion measures compiled by Afrin and Yodo.

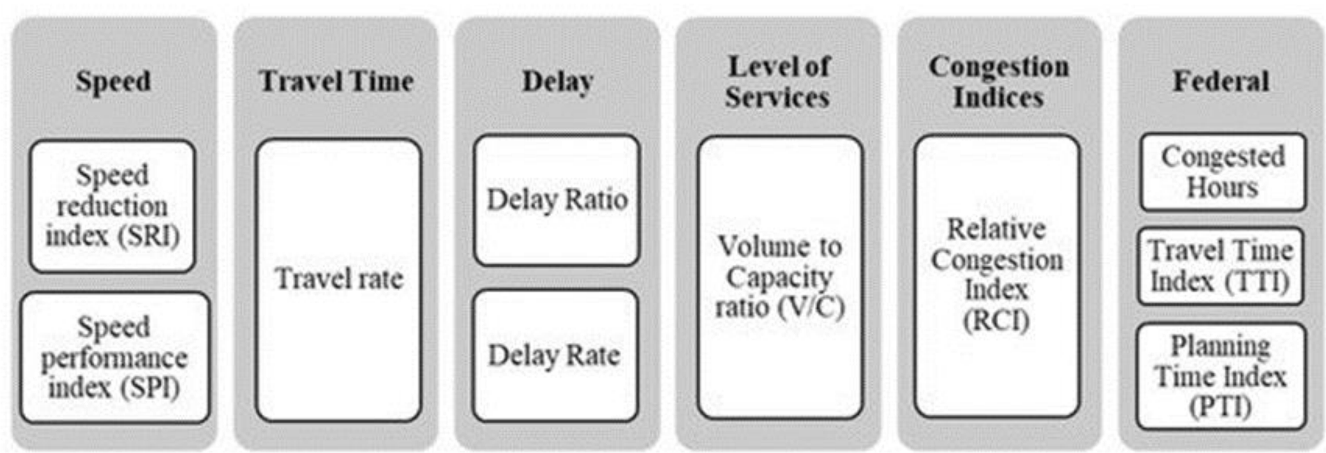


Figure 5. Current approaches to measure congestion (Afrin and Yodo 2020).

Table 2. Advantages and disadvantages of congestion measures (adapted from Afrin and Yodo 2020).

Category	Measurement Approach	Congestion Range	Advantages	Disadvantages
Speed	Speed reduction index (SRI)	>4	Easily comprehensible; provides information about relative speed in normal and congested conditions	Does not consider nonrecurring conditions
	Speed performance index (SPI)	Different range levels		
Travel Time	Travel rate	No range available	Both time and space are accounted for	Capacity is not included
Delay	Delay rate	No range available	Can be used to estimate system performance and choose efficient travel method	Limited for a specific road type; no suggested congestion range
	Delay ratio	No range available	Compares relative congestion levels in different types of roads	
Level of Service (LOS)	Volume to capacity ratio	Different range levels	Comprehensible by non-technical users	Cannot provide continuous congestion value; no

Category	Measurement Approach	Congestion Range	Advantages	Disadvantages
				information on speed and time are considered
Congestion indices	Relative congestion index (RCI)	>2	Spatial-mean performance of traffic is represented	Limited to particular road type
	Road segment congestion index	No range available	Appropriate to represent segment condition	Only applicable to measure specific segment conditions
Federal	Congested hours	No range available	Provides an estimate of the congested time period	Only depends on speed
	Travel time index (TTI)	No range available	Accounts for recurring congestion; both time and space are considered	Value could vary due to different peak period considerations
	Planning time index (PTI)	No range available	Describes travel time reliability to planners as well as network users	Planning for additional travel time might not always be reliable

Berrouk et al., (2020) consider the aforementioned criteria for assessing traffic congestion and uses a fuzzy inference-based method that incorporates the uncertainty of the independent congestion measures. This method combines three independent measures: the speed ratio, the volume to capacity ratio, and the decreased speed ratio. Transportation professionals frequently combine these measures of traffic congestion into one output that is a composite congestion measure. They suggest that each of the independent measures uses precise thresholds to describe a particular aspect of the traffic conditions, though they may have a high possibility of error, potentially misrepresenting the real traffic condition. However, the suggested fuzzy inference approach takes into consideration every little variation in the input congestion measures and provides a more accurate representation based on language that better reflects the traveler perception of traffic conditions. The suggested analysis method can be used to evaluate the congestion over road sections, arterials, or highway road networks, and the proposed model could be expanded to incorporate other factors playing a considerable role in changing the traffic condition such as parking in streets, road structures, etc.

Rao et al., (2012) give an overview and present possible ways to identify and measure metrics for urban arterial congestion. A systematic review covers distinct aspects like definition and discusses the strengths and weaknesses of these measures (see Table 3 and Table 4). Considering the different desirable attributes for a congestion measure suggested by the researchers, congestion is a function of a reduction in speeds, which is the direct cause of loss of time and leads to increased vehicle operating costs, fuel consumption, and emissions of air pollutants and greenhouse gases (GHGs). Therefore, the setting of a threshold that is directly related to travel speeds is most appropriate.

Table 3. Congestion metric evaluation matrix (Rao et al., 2012).

	Assessment Criteria						
Congestion Metric	*Simplicity*	*Ease of Data Collection*	*Stability*	*Repeatability*	*Magnitude of Congestion*	*City Comparison*	*Continuous Value*
Speed	Y	Y	Y	Y	Y	N	Y
Travel Time	Y	Y	Y	Y	N	N	Y

Delay	N	N	N	Y	N	N	Y
LOS and Volume	Y	Y	N	Y	N	N	Y

Table 4. Advantages and limitations of macro level indices for congestion (Rao et al., 2012).

Macro Level Indices	**Advantages**	**Limitations**
Travel time and delay	• Time-based congestion measures provide guidance on identifying major issues. • Travel time index has the advantage of expressing traffic congestion in terms of both space and time. • It is easy for public to understand the main concept of this index.	• The use of ratio measures is limited for a particular road type or facility and the values cannot be used effectively for a geographic area. • Congested travel or congested roadway length does not represent the different magnitude of congestion. • Travel time index requires separation of recurring and incident delay. Measurement of non-recurring data can be difficult.
Volume and LOS	• The main advantage of LOS is that most non-technical audiences can understand it. • The representative variable in traffic flow analysis. • Widely used because it is very easy to collect this data.	• LOS cannot provide a continuous range of values of congestion, and these methods provide no distinction between different levels of congestion once congested conditions are reached. • LOS only represents location-specific congestion phenomenon and does not reflect overall or regional congestion condition. • LOS is sometimes misleading, especially when the condition is near a threshold.
Speed	• It can be used to illustrate the reduction in mobility people experience during congestion. • Compared in congested and free-flow cases. • The duration of congestion can also be determined by measuring the reduced travel speeds over a specific time period. • Travel speed is relatively easily obtained from model forecast data, and may also be directly observed through field surveys. • Data collection using latest technology like GPS which is effective and economical technology can be applied and these data easy integrated with Geographical Information System. • This data may be summarized at any analysis level desired: link, corridor or regional-wide.	• The use of a range of speeds for entire study area reflects the lack of consensus among urban areas as to the appropriate threshold, which reflects local conditions. • Result is relative to free-flow speed, which is difficult for motorists to comprehend.

Boarnet et al., (1998) developed a traffic congestion index based on capacity adequacy data and used this technique to yield a congestion measure (dataset for California highways from 1976 through 1994). This method started with some measure of congestion that is not truncated as truncated measures cannot distinguish very severe congestion and moderate congestion.

$$CA = \left(\frac{rate\ volume\ capacity}{volume\ during\ present\ design\ hour}\right) * 100$$

As illustrated in the equation above, capacity adequacy (CA) is the ratio of the highway's rated capacity divided by a measure of peak hour travel flow (volume during the present design hour), multiplied by 100. Larger CA values mean less congestion. Developing a county congestion index includes two steps of aggregating CA to the county level: CA is calculated for each highway and then for each county.

Results suggest that the variable of congestion measures for each county are a useful indicator of congestion within geographic areas and over time. The potentially important application of congestion indices is their use on individual links in a highway network. Congestion indices can only measure highway network performance and do not suggest policy solutions. Future research should examine the expansion of the HPMS dataset to better support congestion indices throughout the U.S. and the implications of different measures of capacity and the distinction between peak hour and daily volume.

Recurrent and Non-recurrent Congestion

Traffic congestion is characterized and measured as being recurrent or non-recurrent. Dowling et al. (2015) state that recurrent congestion is estimated by using *Highway Capacity Manual* (TRB 2010) speed-flow curves and data on facility demands, free-flow speeds, and capacities. Non-recurrent congestion is estimated in terms of annual vehicle hours of delay caused by weather, work zones, incidents, and so forth. The methodology employs incident probability trees, incident duration (sensitive to surveillance and response times), and estimates of remaining capacity during incidents to estimate incident delay. Weather- and work-zone-related delays are estimated on the basis of frequency of occurrence and estimates of capacity reductions during periods of bad weather and work-zone activity (Dowling et al., 2015). Figure 6 illustrates the primary causes of recurring and non-recurring congestion.

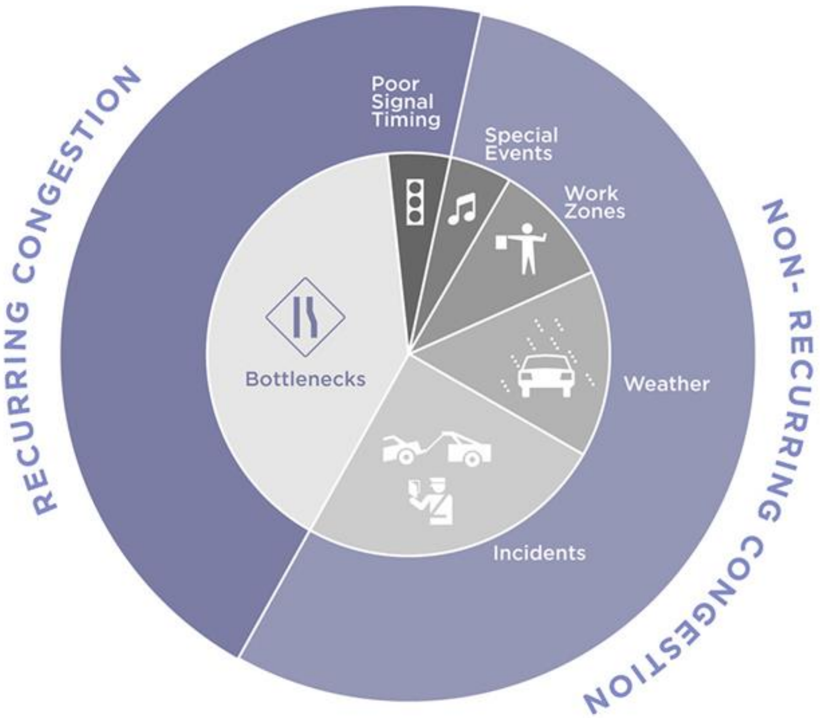


Figure 6. Causes of congestion (Dowling et al., 2015).

Tariq et al. (2020) investigated and assessed automating the process of updating the signal timing plans during non-recurrent conditions by capturing the history of the responses of the traffic signal engineers to non-recurrent conditions and utilizing this experience to train a machine learning model. A combination of recursive partitioning and regression decision tree (RPART) and fuzzy rule-based system (FRBS) (see Figure 7) was utilized to deal with the vagueness and uncertainty of human decisions. Comparing the decisions made based on the resulting fuzzy rules from applying the methodology with previously recorded expert decisions for a project case study indicates accurate recommendations for shifts in the green phases of traffic signals. The simulation results indicate that changing the green times based on the output of the fuzzy rules decreased delays caused by lane blockages or demand surge.

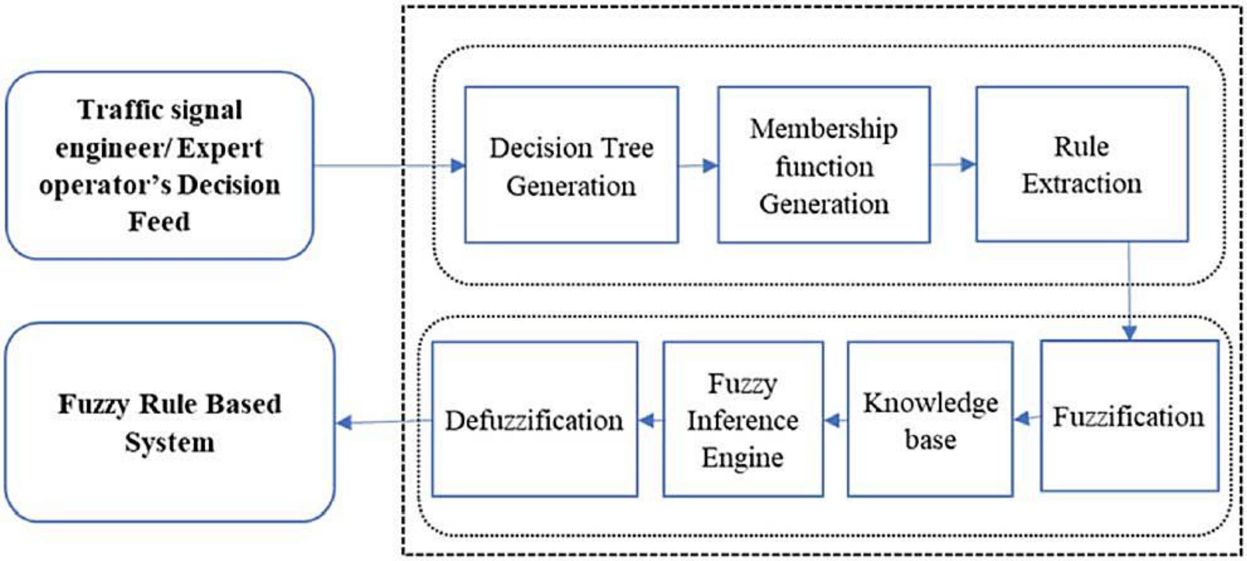


Figure 7. Principal steps of the fuzzy rule-based decision system utilized (Tariq et al., 2020).

Song (2019) investigated the use of a data-driven procedure for quantifying spatiotemporal recurrent congestion impact. This study used spatiotemporally historic congestion information and generated stochastic spatiotemporal congestion distributions in terms of congestion types. Using the relationship between the distributions of recurrent and non-recurrent congestion occurring at bottlenecks, the bottleneck impacts were estimated by capturing spatial and temporal impact of a recurrent bottleneck from that of non-recurrent congestion occurring at recurrent bottleneck. The proposed approach represents a significant improvement in the understanding and monitoring of mobility on freeways. This approach can be directly applied to evaluate and rank bottlenecks.

Qi et al. (2019) used rank measurement based on speed to identify bottlenecks. They used an identification procedure consisting of three steps:

(1) the rank distribution is fit using Gaussian Mixture Model (GMM),
(2) the Kullback–Leibler (KL) divergence is employed to measure the similarity between adjacent links; and
(3) the bottleneck areas are clustered. Using rank information would enhance the bottleneck identification performance.

Skabardonis et al. (2003) describes a methodology and its application to measure total, recurrent, and nonrecurrent (incident related) delay on urban freeways. Random delay was measured in the performance management system as the excess vehicle-hours traveled below a reference speed. To obtain a statistical characterization of this delay, a probability model was established. Distinguish between non-incidents (I=0), non-accident incidents (I=non), and accidents (I=acc), and the basic relation is shown as:

Total congestion = Recurrent congestion + Non-recurrent congestion.

Non-recurrent congestion delay is found to be between 13 to 30 percent of the total delay. The percentage of non-recurrent delay depends on the extent of recurrent delay. Non-recurrent delay will account for 100% of total delay if no recurrent delay. The applications considered here deal with peak periods in freeways with significant recurrent congestion. The methodology can be used to derive estimates of average travel times and travel time variability and propose travel time reliability measures.

Anbaroğlu et al. (2015) proposes two novel methods for non-recurrent congestion (NRC) event detection on heterogeneous urban road networks based on link journey time (LJT) estimates. The way in which the identified NRCs are represented would allow a researcher to observe the evolution of an NRC in space and time. Percentile-based NRC detection aims to capture the heterogeneous nature of an urban road network by relying on the percentile values of the estimated LJTs. It is observed that lognormal distribution is the most suitable way to model the estimated LJTs. A modified version of expectation-based space-time scan statistics (STSS) as described in Neill (2008) for the purpose of detecting NRCs. The method consists of four main steps, which are summarized in Figure 8. Both NRC detection methods have been evaluated with different parameter settings on London's urban road network. Link-based analysis demonstrate the effectiveness of the proposed methods on links whose LJTs exhibit high variance.

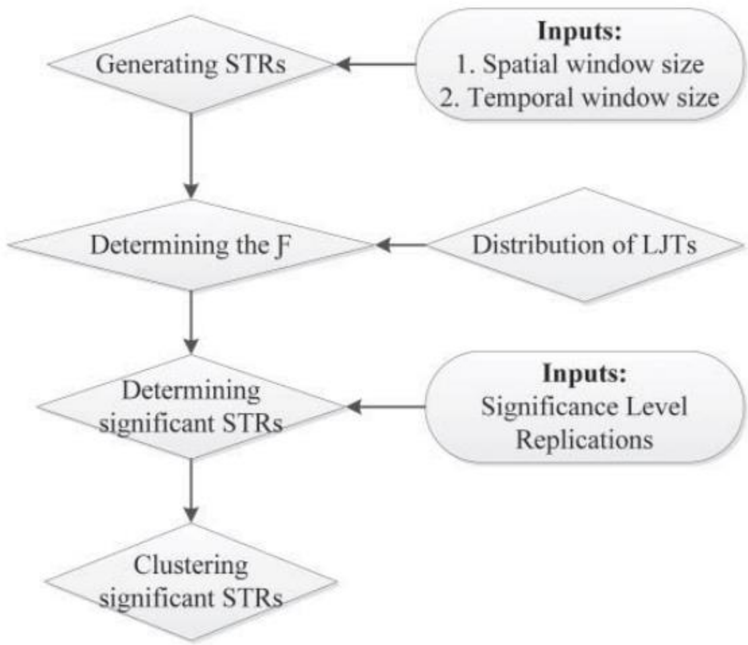


Figure 8. Methodology for detecting non-recurrent congestion by space-time scan statistics (Anbaroglu et al., 2015).

Data and Congestion Management

The following sections provide a summary of the utilization of data in the ongoing efforts of congestion management.   Of note is the discussion on real-time and third-party data that can offer support enhanced decision making related to the proactive deployment of active traffic management (ATM) strategies for congestion management.

Bluetooth/Wi-Fi/Probe Data

FHWA has procured probe data feeds and provides free access to state and local agencies as National Performance Measures Research dataset (NPRMDS). INRIX is the current provider of NPMRDS data records. Some advantages and limitations of INRIX are as follows:

- In terms of geographic coverage, INRIX has been evaluated for interstates and non-interstates and has been shown to be reliable for almost all times of day on interstates.
- INRIX is more reliable during the day than at night, especially during peak hours.
- Regarding incident detection, INRIX is reliable for detecting merely congestion, especially recurring congestion. Generally, two types of congestion exist: recurring and nonrecurring. Recurring congestion is regarded as the congestion caused by the routine traffic in a normal environment which is somehow expected, whereas nonrecurring congestion is unexpected and is most likely caused by an incident. Nonrecurring congestion may emerge because of a variety of factors such as blocked lanes, crashes, disabled vehicles, work zones, lane closures, adverse weather conditions, etc. When INRIX detects congestion, it obtains all of the information related to the congestion, such as the duration of the congestion and its location.
- A time delay (latency) for INRIX congestion detection is common.

Ahsani et al. (2020) evaluated the reliability of probe-sourced data (INRIX) using two performance measures: congested hour and the number of congested events. Wavetronix sensors were used to collect benchmark data consisting of high-resolution traffic data every 20 seconds. For this study speed was the only traffic parameter used from Wavetronix sensors and INRIX segments. Researchers used a point change detection algorithm that delivered a higher accuracy and significantly improved congestion detection compared to the traditional fixed-threshold method (Ahsani et al., 2020).

Mandal et al. (2011) developed an Intelligent Traffic Congestion Monitoring & Measurement System called TrafficMonitor to monitor and measure the road traffic congestions using probe vehicle that combines active RFID (based on IEEE 802.15.4 protocol, 2.4 GHz ISM band) and GSM technologies. The congestion detection algorithm is based upon calculation of vehicular speed over a stretch of road and the average waiting time of vehicles at road crossing. Characteristics of this algorithm include the following:

- One active RFID tag to be kept in the probe vehicle;
- One wireless router (R) and one wireless coordinator (C) (both acting as RFID readers) to be installed at the roadside, around 200mt apart, for calculating average trip time to cross the two road-side units, average waiting time of vehicles at that stretch of the road and sending the measurement to the central monitoring station;
- Two GSM modems (one with coordinator and the other with central monitoring station) for wireless data transmission between gateway and software monitoring system;
- Monitoring station software for real-time visualization of traffic congestion and report generation. The software is also capable of supporting multiple unit system instances simultaneously; and
- The system can also be connected wirelessly with variable message sign (VMS) to divert the traffic upon automatic detection of congestion on a stretch of a road (Mandal et al., 2011).

The goal of the algorithm is to implement a system that would trace the travel time of probe vehicle as it passes the roadside devices, create an average trip time. Figure 9 shows the overall system architecture to measure congestion across the stretch between J1 and J2 ("C" and "R"). A wireless gateway and wireless router are installed at the roadside and the red vehicle is the probe vehicle which carries an active RFID device. Figure 10 illustrates the data flow sequence for the project.

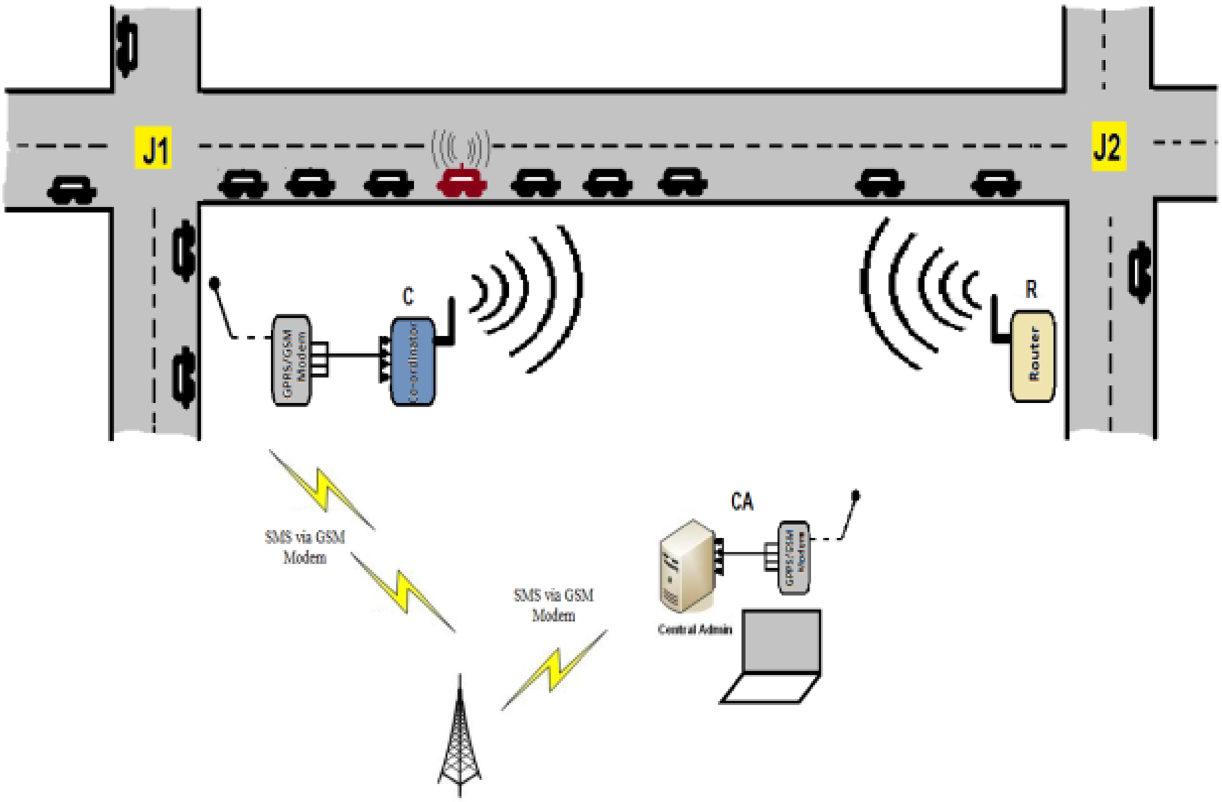


Figure 9. System diagram (Mandal et al., 2011).

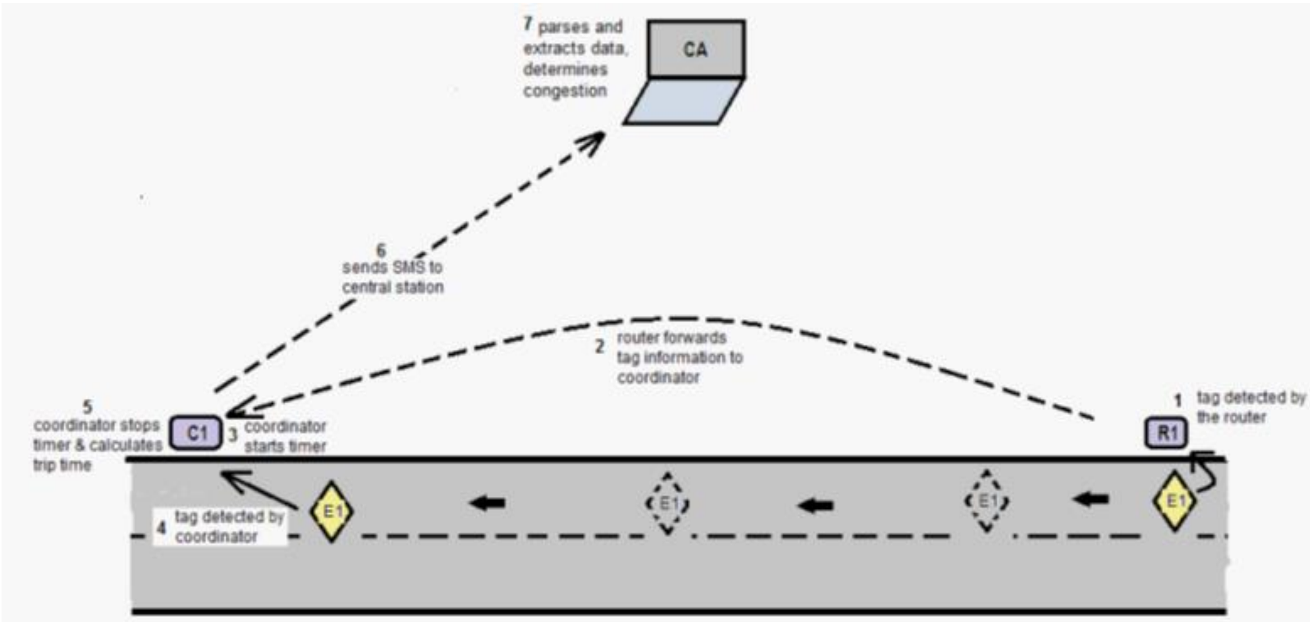


Figure 10. Data flow sequences (Mandal et al., 2011).

Jin et al. (2020) evaluated the new models from Toyota in Japan, China, and the United States that will be connected with routing function switching from the embedded device to the cloud in which there are plenty of probe data uploaded from the vehicles. Probe data makes it possible to analyze user preferences and customize routing profile for users. This paper describes a method to analyze the user preferences from the probe data uploaded to the cloud. The method includes data collection, the analysis model of route scoring and user profiling (Jin et al., 2020).

A study by Khattak et al. (2020) was conducted along an urban corridor in Pittsburgh, PA consisted of 23 intersections in Pittsburgh to evaluate the operational impacts of the scalable urban traffic control (SUTRAC) adaptive signal control technology (ASCT). The research team used a combination of real-world GPS floating car runs and private sector probe data from INRIX to assess the impact of the ASCT. Data were collected with the ASCT active and inactive to determine the operational impacts on the mainline and cross streets. The ASCT was found to produce significant improvements in the number of stops made along the corridor. Six months of private sector probe data was used to examine travel time reliability along the corridor, and reliability was also found to have improved. Furthermore, Bayesian models were calibrated to account for variations in speeds and acceleration/deceleration. The Bayesian models revealed that driving was less volatile with the ASCT system in operation over instantaneous periods, which also points towards improved operations. The findings of this study are generally consistent with past evaluations of other ASCTs, indicating that the SURTRAC system is another potential tool for managing congestion on signalized urban arterial networks (Khattak et. al., 2020).

Mohammadi et al. (2020) developed a technique for using Bluetooth signals transmitted by both stationary and moving beacons, creating radio maps, and applying an algorithm called k-nearest neighbors. Four Bluetooth signal scanners and a beacon were used in the experiments in an intersection and its adjacent streets. The researchers found that although positioning of stationary beacons can be achieved with a precision of up to 90% with an error of 5 m or less if the stations and scanners are properly arranged, the positioning of moving beacons is more challenging.

Cotton et al. (2020) conducted a study in Baton Rouge, LA using performance metrics such as match rate, travel time, and segment speed through analyzing collected data from several Bluetooth devices - two advanced Bluetooth devices coupled with classic Bluetooth technology: the demodulator (BT DM), and the low-energy Bluetooth signal additional component (BLE). Data were collected along a 0.59-mi segment of interstate and along a 0.52-mi segment of an urban arterial road. The data collected were compared with benchmark data sets, gathered during the same period, using manual counts from video footage, radar data, and floating car data (FCD). Comparative analysis showed that BLE produced significantly higher matched rates than BT DM and was able to maintain higher accuracy with increased levels of detection. Results of a Kruskal–Wallis test showed BT DM to have a statistically significant difference with FCD during only one out of three peak periods along the interstate segment. However, BLE matched closest with FCD along the interstate, but shared a significant difference with the benchmark data set during two peak periods along the urban arterial roadway. Considering the level of detection with the accuracy of travel times and segment speeds when compared with the benchmark data, it was evident that the BLE performed better than the BT DM (Cotton et. al. 2020).

A study conducted by Zhang et al. (2020) to evaluate the accuracy of the travel time data estimated by Dual loop, Waze, HERE, and INRIX against Bluetooth data on multiple segments of the I-80 freeway between Davis and Sacramento, CA. The researchers conducted a simulation-based critical sampling rate analysis, which suggests that the Bluetooth travel time data qualifies for approximating the ground truth. The evaluation methods and derived indices, travel time error bias (TEB), average absolute travel time error (ATE), and standard error of mean (SEM), were applied to compare the travel time data reported by Waze, HERE, and INRIX with the benchmark (Bluetooth) data. Moreover, all three vendors' data accuracy deteriorates when the traffic congestion intensifies (Zhang et al., 2020).

Santa et al. (2020) presented advances towards a communication unit for personal mobility vehicles with embedding and power constraints, in a design provided with low-power wide area network (LPWAN) communications and several sensors to enable smart urban services. Long range wide-area network (LoRaWAN) and narrow band internet of things IoT (NB-IoT) transceivers were included. The main contributions of the research include, but are not limited to:

- LPWAN-based onboard Unit (OBU) architecture to include personal mobility devices into the IoV;
- Multi-RAT LPWAN communication unit with LoRaWAN and NB-IoT;
- OBU prototype with communication and sensor capabilities to be exploited in pollution and mobility services; and
- Performance evaluation of NB-IoT in mobile urban scenarios.

The OBU prototype was tested under real settings and main performances obtained with NB-IoT. Although coverage results revealed fair signal-to-noise ratio (SNR) with some communication gaps, delay and packet losses remain low, with 131.40 milliseconds (ms) of round-trip delay Time (RTT) and 0.32 % of block error rate (BLER), which encouraged the research team to use this technology not only for monitoring services, but also for those requiring a reliable and low-latency communication channel. Hence, as compared to our previous works with LoRaWAN, NB-IoT scales worse per base station and consume more energy, but offered clear advantages in terms of quality of service (Santa et al., 2020).

Researchers conducted a numerical experiment (Yang et al., 2019) based on a simulation model calibrated with the field loop detector data on IH-894 in Milwaukee, Wisconsin. A proposed traffic state estimation model using Lagrangian-space Kalman filter is based on the travel time transition model (TTM). The proposed TTM-based method is compared with a CTM-based Kalman filter estimator on Eulerian coordinate under different penetration rates of the input Bluetooth, Wi-Fi, or Cellular probe vehicle data in which vehicles are re-identified between two consecutive physical or virtual readers. The evaluation results indicated that the TTM-based estimation model performed well especially during congestion and could track traffic breakdowns and recovery effectively. The TTM-based estimator outperformed CTM-based methods at all penetration rates levels. Furthermore, the 4% penetration rate was found to be a threshold beyond which TTM-based estimation results improved significantly. With increased penetration rates, the TTM-based model can achieve a mean absolute percentage error around 10%; while CTM-based model remains higher than 13% (Yang et al., 2019).

The method used by Advani et al. (2019) focused on challenges to automate the generation of Bluetooth MAC Scanner (BMS) links by integrating the Bluetooth scanners and the Open Street Map network used for congestion visualization in dashboard and that can be suitable for business intelligence. The state-of-the-art method for developing the BMS based network consisted of a restricted path matching technique with a 250 meters radius buffer zone thereby extracting all the points intersecting between the buffer boundary and the base line road layer. The intersecting points were defined as an intercept vector and were used as reference points to trace the link among sensors. Thus, for developing these links, distance based shortest path algorithm was adopted using one to many approaches. In this way, a path with minimum cost (distance) was extracted and a layer file was then generated. The paper provides a QGIS model used to automatize the process of creating a network layer for a set of scanners. The stated methodology was tested on a network considering seven sensors, connecting four major intersections from the city network. The results were considerable, and the method was extended to develop BMS based links for the entire Brisbane city network. The extracted network was utilized to develop congestion visualization plots using tableau platform. Lastly, the results were exploited to rank the BMS links based on their level of congestion for different duration of the day. Thus, the stated method is convincing as well as ready to implement for any large city network (Advani et al. 2019).

Liu et al. (2020) used approximately two million records of Bluetooth time-stamped media access control (MAC) data to evaluate their accuracy for travel time. The work demonstrated that accurate Bluetooth-based travel time information on signalized arterial roads can be derived if an appropriate matching method can be selected to smooth out the remaining noise in the filtered travel time estimates.

A study conducted by Yuan et al. (2019) included a review of case studies regarding the use of Bluetooth for traffic data and included three case studies in Delaware. Some of the issues found with using Bluetooth data are as follows:

- Unknown location of detected vehicle within the detection zone;
- Extremely dense data processing;
- Communications/power supply complications during sensor deployment;
- Oversampling;
- Unable to determine traffic volume;
- Trip-chaining;
- Low detection/match rates;
- No standard for of analysis;
- Limited information extraction; and
- Difficulty of determining reasons for delay.

The overall conclusion was that the Bluetooth technology by itself was not a proper tool for travel time measurements. However, several studies highlighted that integrating Bluetooth traffic data with other types of data, such as data collected by ALPR technology, or GPS, can help researchers to achieve more accurate and comprehensive measurements on travel time information (Yuan et al., 2019).

Researchers from the University of Central Florida (Abdel-Aty et al., 2019) developed a decision support system (DSS) for integrated active traffic management (ATM) for both freeways/expressways and arterials/collectors. The data sources used included HERE, NPMRDS, MVDS microwave vehicle detection system (MVDS), automatic vehicle identification (AVI), BlueTOAD, BlueMAC, etc. All data were processed to reflect traffic for the same segment at the same time and evaluated with the consideration of accuracy and availability. Fusion algorithms were developed to improve the data accuracy as well. The appropriate data were used to identify the critical roadways and segments which experienced serious traffic congestion and travel time unreliability. Around 600 miles roadways, with around 1,200 segments in total, were evaluated based on measures reflecting traffic efficiency and reliability. Two critical corridors (i.e., I-4 corridor in Downtown Orlando and SR-417 corridor in East Orlando) were selected for developing the DSS for integrated ATM. By using Aimsun Next, the research team has developed a dynamic traffic assignment (DTA) simulation platform, involving multi-resolution modeling (MRM) framework. The platform is the largest DTA-based simulation network attempted in the United States. The microscopic simulation models were developed to test integrated ATM control strategies. Based on the developed simulation platform, different integrated ATM control strategies, including variable speed limit (VSL), queue warning (QW), ramp metering (RM), and their combinations were tested under three different congestion levels on both corridors. Two METANET models were developed to predict traffic conditions. The DSS was developed for the integrated ATM controls by balancing the traffic on both freeways/expressways and arterials/collectors. A total of 420 simulation runs were conducted to evaluate the developed DSS of integrated ATM, and the generic rules of integrated ATM controls were summarized for implementation. The results suggested that the developed DSS could successfully reduce traffic congestion and improve travel time reliability (Abdel-Aty et al., 2019).

Tahmasseby (2015) conducted research to estimate travel time and speed with the output of BluFAX sensors. Study results showed that Bluetooth technology as the benchmark was able to provide reliable traffic data for the selected study corridors for short study periods but had constraints and difficulty to analyze and process its generated massive data records in long study periods. Crowdsourcing technique can be a viable alternative and provide travel time reliability estimates with a reasonable accuracy, but the number of observations was much lower than that of BluFAX. Therefore, further research is needed to verify the accuracy of crowdsourcing technologies such as TomTom for travel time studies.

Lewandowski et al. (2018) proposed a method, which utilized mobile devices (smartphones) and Bluetooth beacons, to detect passing vehicles and recognize their classes. It allowed detecting three classes of vehicles (personal cars, semitrucks, and trucks) by analyzing strength of radio signal received from BLE beacons. Advantages of the introduced method were demonstrated during experimental evaluation in real-traffic conditions. Extensive experiments were conducted to test different classification approaches and data aggregation methods. During experiments the classification accuracy was compared for several RSSI-based traffic monitoring approaches. Initial experiments were conducted to calibrate parameters of the algorithms. In these experiments, vehicle classification was performed with use of 8 aggregates (minimum, maximum, difference between max. and min., mean, standard deviation, median, Pearson correlation coefficient, and number of received frames). At the next step, the most effective set of attributes was selected with use of the backward elimination method. Also, this research also aims to increase the accuracy of vehicle detection by using the proposed classifier ensemble in combination with majority voting.

Basic Safety Messages and Connected Vehicles

A basic safety message (BSM) consists of a packet of data containing information about vehicle position, heading, speed, and other information relating to a vehicle's state and predicted path (see Figure 11). The BSM contains no personally identifying information (PII). Connected vehicle safety applications will enable drivers to have 360-degree awareness of hazards and situations they cannot even see (USDOT). Connected vehicle technologies also enable vehicles, roadside infrastructure, and personal portable devices to communicate and share information through wireless communication technology. Onboard units (OBUs) installed on vehicles will continually broadcast BSMs. These messages are received by other vehicles and used by applications to improve safety. Roadside units (RSUs) installed along the roadway will also receive and broadcast messages to further improve safety and enhance mobility. The correctness and reliability of messages being transmitted between devices is of critical importance as it impacts the outcomes and effectiveness of safety applications based on them. Connected vehicle devices sending messages need to digitally sign their messages, and the receiving devices need to verify the signature before acting on it. To enable security in vehicle-to-everything (V2X) systems, it is important to ensure:

- A message originates from a trustworthy and legitimate device;
- A message was not modified between sender and receiver; and
- Misbehaving units are detected and removed from the system (USDOT 2019).

Connected V2V safety applications are built around the SAE J2735 BSM, which has two parts.

- Part 1 contains the core data elements (vehicle size, position, speed, heading acceleration, brake system status) transmitted approximately 10x per second.
- Part 2 is added to part 1 depending upon events (e.g., ABS activated) and contains a variable set of data elements drawn from many optional data elements (availability by vehicle model varies). This data is transmitted less frequently.

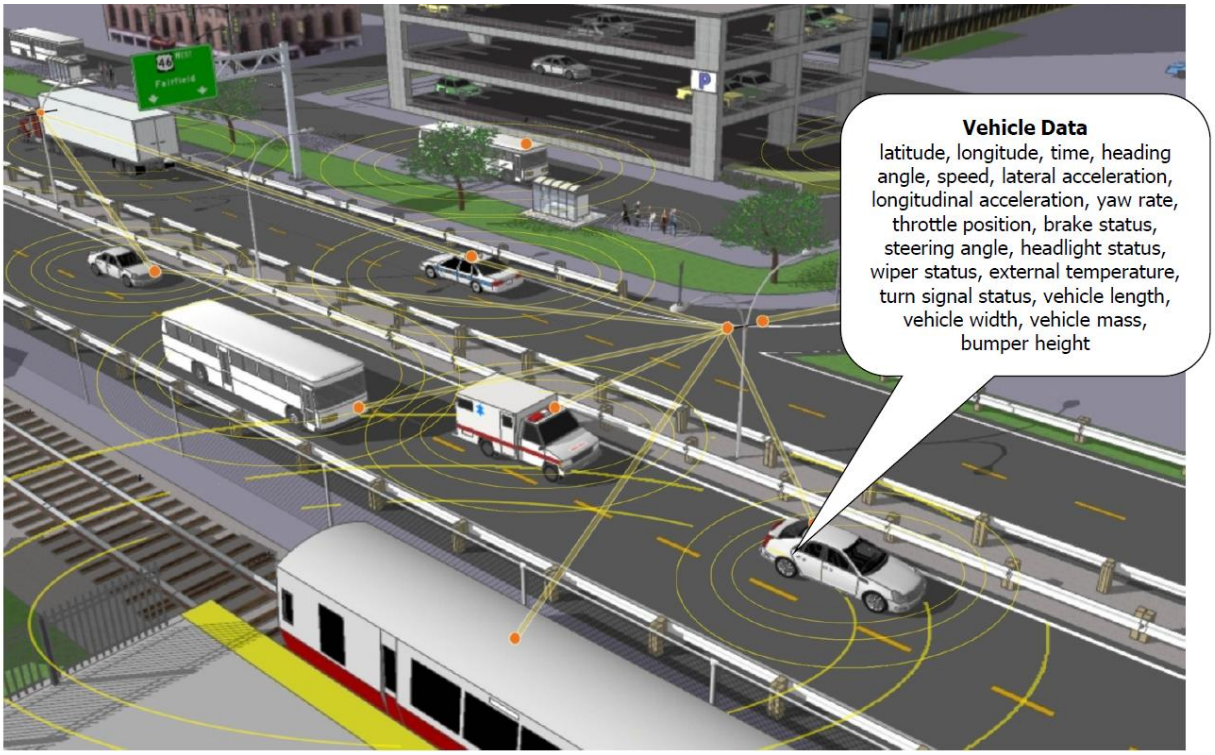


Figure 11. Fully connected vehicle (Cronin 2020).

The BSM is transmitted over dedicated short-range communications (DSRC) (range ~1,000 meters) and there is no on-vehicle BSM storage of BSM data. The BSM is tailored for low latency, localized broadcast required by V2V safety applications. Augmenting BSM with key Part 2 elements via cellular data provides the vehicle data needed to support nearly all mobility applications, including:

- Cooperative adaptive cruise control;
- Dynamic speed limits (also known as speed harmonization);
- Queue warning;
- Intelligent traffic signal systems;
- Transit signal priority;
- Mobile accessible pedestrian signal system;
- Emergency communications and evacuation;
- Incident scene pre-arrival staging guidance for emergency responders;
- Incidents scene work zone alerts for drivers and workers;
- Next generation integrated corridor management;
- Transit connection protection;
- Dynamic transit operations;
- Dynamic ridesharing;
- Freight traveler information; and
- Traveler information (Cronin 2020).

Through BSM data from the Michigan Safety Pilot Program, (Kamrani et al., 2020) applied a Markov Decision Process (MDP) framework to understand driving behavior in terms of acceleration, deceleration and maintaining speed decisions. Personally revealed choices (PRC) that maximize the expected sum of rewards for individual drivers were obtained by analyzing detailed data from 120 trips and the application of MDP. Specifically, this paper defined states based on the number of objects around the host vehicle and the distance to the front object. Given the states, individual drivers' reward functions were estimated using the multinomial logit model and used in the MDP framework. Optimal policies (i.e., PRC) were obtained through a value iteration algorithm. The results showed that as the number of objects increases around a host vehicle, the driver preferred to accelerate to escape the crowdedness around them. In addition, when trips were segmented based on the level of crowdedness, increased levels of trip crowdedness resulted in a fewer number of drivers accelerating because the traffic conditions constrain them to maintaining constant speed or deceleration. One potential application of this study is to generate short-term predictive driver decision information through historical driving performance, which can be used to warn a host vehicle driver when the person substantially deviates from their own historical PRC. This information could also be disseminated to surrounding vehicles as well, enabling them to foresee the states and actions of other drivers and potentially avoid collisions.

A set of models to realistically generate cooperative awareness messages (CAMs) or BSMs in vehicular networks were developed using traces collected by Volkswagen and Renault in urban, suburban, and highway test drives under normal road traffic conditions. The models are based on m^{th} order Markov sources, the model size of CAMs, and the time interval between CAMs. The models are openly provided to the community and can be easily integrated into any simulator (Molina-Masegosa et al., 2020).

Wang et al. (2017) presented an online traffic condition evaluation model utilizing V2X communication using the Analytic Hierarchy Process (AHP) and the multilevel fuzzy set theory to fuse multiple sources of information for prediction. The vehicle data from the On-Board Diagnostic (OBD) was fused with the static road data in the Roadside Unit (RSU) and the real-time traffic evaluation scores were calculated using the variable membership model. The real data collected by OBU in field test demonstrated the feasibility of the evaluation model. Compared with traditional evaluation systems, the proposed model can handle more types of data but demands less data transfer.

Heaslip et al. (2020) assessed the capacity changes due to the introduction of connected vehicles (CVs) and automated vehicles (AVs) on Virginia freeway corridors. The three vehicle types used in the mixed traffic scenarios included legacy vehicles (LVs), vehicles equipped with adaptive cruise control (ACC) (AVs), and vehicles equipped with cooperative adaptive cruise control (CACC) (connected and automated vehicles [CAVs]). Each scenario included light-duty passenger vehicles and heavy vehicles (HVs) with AV and CAV capabilities to determine their overall effect on capacity. AVs and CAVs proved capable of improving highway operations. Even in the presence of high percentages of HVs and steep grades, vehicles equipped with AV and CAV technologies provided better performance than LVs.

Lin et al. (2019) proposed a compressive sensing (CS) approach that allows CVs to capture and compress data in real-time and later recover the original data accurately and efficiently. The approach was evaluated using two case studies:

- Recapture 10 million CV basic safety message (BSM) speed samples as well as other BSM variables; the results show recovery of the original speed data with root-mean-squared error as low as 0.05 MPH; and

- Freeway traffic simulation model built to evaluate the impact of the approach on travel time estimation; multiple scenarios with various CV market penetration rates, on-board unit (OBU) capacities, compression ratios, arrival rate patterns, and data capture rates were simulated.

Results showed that the approach provided more accurate estimation than conventional data collection methods by achieving up to 65% relative reduction in travel time estimation error. With a low compression ratio, this approach can still provide accurate estimation, therefore reducing OBU hardware costs. This approach can also improve travel time estimation accuracy when CVs are in traffic congestion as it provides a broader spatial–temporal coverage of traffic conditions and can accurately and efficiently recover the original CV data (Lin et. al. 2019).

Shelton et al. (2019) used traffic modeling software to develop and test a vehicle mimicking the behaviors of several automated and connected vehicle (CV) applications in a congested and complex urban network. The algorithm behind the CV ran a suite of mobility-focused applications, inspired by cooperative adaptive cruise control (CACC), speed harmonization, and queue warning applications. The CV was first tested on a small sample network, consistent with approaches obtained from a review of the literature. The research team then sought to understand the potential effects of CV technology on congestion and mobility in a DTA Texas context by modeling the traffic impacts of CVs at varying market penetrations on a twelve-mile section of I-35 in Austin at 2035 population levels. Researchers used a multi-resolution modeling (MRM) methodology, which incorporates macroscopic, mesoscopic, and microscopic models.

Yu and Fan (2019) presented an optimal variable speed limit (VSL) strategy in a connected autonomous vehicle (CAV) environment for a freeway corridor with multiple bottlenecks. The VSL control was developed by using an extended cell transmission model (CTM) which accounted for capacity decrease and mixed traffic flow, including traditional human-driven cars and heavy vehicles, and autonomous vehicles (AVs). A multiple-objective function was formulated which aims to improve the operational efficiency and smooth the speed transition. A genetic algorithm (GA) was adopted to solve the integrated VSL control problem. A real-world freeway stretch was selected to test the designed control framework. Sensitivity analyses were performed to investigate impacts of both the penetration rate of CAVs and communication range. Simulation performances demonstrated that the developed VSL control not only improves the overall efficiency but also reduces tailpipe emission rate. Simulation results also showed that the VSL control integrating vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and infrastructure-to-vehicle (I2V) communication outperforms the VSL control only. In addition, as the penetration rate of CAVs increases, better performance can be achieved (Yu & Fan, 2019).

Maitipe et al. (2012) described the architecture, functionality and the field demonstration result of a newly developed DSRC based V2I work zone traffic information system with V2V assistance. This system can automatically acquire important work zone travel information, for example, travel time and the starting location of congestion and relay them back to the drivers approaching the congestion site. Such information can help drivers in making informed decisions on route choice and preparing for upcoming congestion. The new system is also portable and uses only one roadside unit – dedicated short range communication, which can acquire traffic data by engaging the vehicles traveling on the roadside whether within or outside of its direct wireless access range. From traffic data, it estimates important traffic parameters and periodically broadcasts them back to the vehicles approaching the congestion well before they enter the congested area. The results from the field demonstration have indicated that new system can adapt to dynamically changing work zone traffic environments and can handle much 2 longer congestion lengths as compared to the previous system using V2I-only communication without V2V assistance (Maitipe et al., 2012).

Saxena and Isukapati (2019) proposed a simulated-BSM concept to enhance safety of transport facilities. An ego-vehicle with local sensor feed capability created a basic safety message for any identified rogue vehicles in its field of view and broadcasted it to infrastructure for implementing efficient and safe control actions. The concept of S-BSM was applied in the context of enhancing safe & efficient operations of rural high-speed signalized intersections. Simulation results suggested that the S-BSM framework can be extremely useful in improving safety of rural transport facilities without compromising for efficiency.

Benaissa et al. (2020) introduced a data reuse model that retains collected BSMs, stores, and processes them inside the vehicle constituting a continuous data source holding retained snapshots along the roadway. In the first stage, this model captured generated and acquired BSMs. Then, in the second stage, it performed a series of procedures on the raw BSMs to be storable according to the proposed model. In the third stage, it aimed at opening up new possibilities for the endless reuse of stored BSMs. In the case study, the research team was able to perform lossless data compression and considerably reduce the data size. Adopting the ANN paradigm, they obtained an accuracy of 0.9988 in carrying out traffic volume prediction and attained the visualization of some data elements to enhance analytics and support decisions-making for transportation.

Radar Data

Alessandretti et al. (2007) described a vehicle detection system fusing radar and vision data and investigated how the results of different sensors can be fused together, benefiting from the best performance of each sensor. Radar supplied different object features, including relative vehicle position and speed. In the first step of the algorithm, radar objects were converted into image reference system that projected radar points onto objects base using mapping transformation, making detection easier and reducing the height of the search area. The intent of the technical paper, which addressed the vehicle detection algorithm, was to filter radar data given by echoes on the guard rail. For the purpose of this research, the guardrail detection method offered positive results both in time savings and in false-positive reduction and could also be improved using tracking.

Nobis et al. (2019) proposed a CameraRadarFusionNet (CRF-Net) method to automatically learn what level of the fusion data is beneficial for the detection result. This method intended to minimize the limitation of sensor data quality in the severe weather conditions, sparsely lit areas, and at night. The BlackIn training strategy was introduced for the fusion of radar and camera data. The authors evaluated the network based on the nuScenes dataset and TUM dataset. Mean average precision scores (mAP) were used for different configurations of the proposed network. The CRF-Net trained with BlackIn achieved a mAP of 0.35 %-points more than without BlackIn. When the network additionally learned on ground-truth filtered radar data (AF, GRF), the mAP advantage of the CRF-Net rose to 12.96 %-points compared to the image baseline (AF). The drop in the mAP score showed that the radar meta data, e.g., distance and RCS, are important for the detection result. The performance gain of the fusion network compared to the baseline (1.4 %-points) was greater for TUM data than for nuScenes. This result was likely a result of the use of three partly overlapping radars in TUM data and the use of a more advanced radar sensor. Also, the superiority of the object detection with the CRF-Net afforded the detection of pedestrians, which are not detected by the baseline network.

Chadwick et al. (2019) demonstrated that incorporating radar data can boost performance on detecting small or distant objects, but conventional neural networks, such as KITTI cannot do that. An efficient automated method for training data generation using cameras of different focal lengths had been introduced. The object detections were from multiple cameras and two classes are included, vehicles and pedestrians/cyclists. In automotive application, distant objects were often in the center of the image which coincided with the overlapped image region, which kept only a small percentage objects were missed. Vehicles were focused on this study because radar signal is poor on pedestrians and good at vehicle detection. There was a significant improvement in the quality of the labels when the combined multi-camera detections were used with the improvement particularly marked for small vehicles. Radar fusion methods significantly improved the detection of smaller vehicles and provided an increase in performance, with the element-wise version outperforming the concatenation method.

Tilly et al. (2020) presented a method related to machine learning to detect and track objects by applying a combination of known feature extractors from lidar and camera detection tasks. a deep neural network architecture (Radar TrackNet) was introduced, which takes radar point clouds from multiple time steps as input to detect road users and to calculate their tracking information. The network was trained and tested on an extensive real-world radar data set. The loss functions chosen for training were binary cross-entropy loss for the confidence branch and root mean squared error (RMSE) loss terms for the track information like the 2D translation and velocity. A comparison to a classification assisted tracker, and a basic clustering tracker was achieved by calculating MOTA and MOTP scores for five tracking scenarios in which the Radar TrackNet achieved the best total score of the three approaches.

Lim et al. (2019) focused on an early fusion of camera and radar sensors and fed a minimally processed radar signal to deep learning architecture along with its corresponding camera frame to enhance the accuracy and robustness of our perception module. FusionNet was presented to extract and combine features extracted from different sensors observing the same space. Two branches were included in FusionNet. Radar branch processed the range-azimuth image from the radar and Camera branch processed the images captured by a forward-facing camera. More than 150,000 synchronized pairs of radar and camera frames, of these frames, 5000 were set aside as the test set in this paper.

For evaluation, FusionNet made a considerable improvement over the Radar only network by taking into account the visual features of the scene. One interesting observation was that mAP score drops much more significantly when the radar input was removed as compared to removing the camera input. The complementary nature of radar and camera signals can be leveraged to reduce the lateral error by 15% when applied to object detection (Lim et al, 2019).

Data Fusion

Transportation infrastructure and vehicles have changed the ability to collect data regarding traffic management. Intelligent transportation system (ITS) infrastructures contain sensors, data processing, and communication technologies that enable the transfer of data from vehicle-to-vehicle, vehicle-to-infrastructure, and infrastructure-to-vehicle and tracking of individual vehicles. Data fusion (DF) is collection of techniques by which information from multiple sources are combined in order to reach a better inference (Faouzi et al., 2011). Transportation agencies are tasked with gathering and analyzing enormous amounts of traffic data, known as big data, across multiple modalities and domains. These data can include traffic cameras, GPS or location information, Twitter and vehicular sensors, taxi trajectories data, metro/bus swiping data, bike-sharing data, etc. (Adetiloye & Awasthi, 2019). Other multisource data includes Bluetooth® and IP-based (cellular and Wi-Fi) communications, global positioning system (GPS) devices, cell phones, probe vehicles, license plate readers, infrastructure-based traffic-flow sensors, and connected vehicles. Table 5 shows the compiled applications, data fusion algorithms and architecture (Faouzi and Klein, 2016). DOTs must rapidly and accurately access, assess, and interpret the data to alert travelers to the existing and impending traffic conditions.

Table 5. Data fusion algorithms and architectures currently applied to ITS (El Faouzi and Klein 2016).

Application	*Data Fusion Algorithm*	*Architecture*
Ramp metering	Fuzzy logic	Sensor level
Pedestrian crossing time	Fuzzy logic	Central-level
Automatic incident detection	Artificial neural network	Sensor level
Automatic incident detection	Bayesian inference	Sensor level
Automatic incident detection	Dempster-Shafer	Sensor level or decision level
Travel time estimation	Inference rules	Sensor level
Travel time estimation	Dempster-Shafer	Sensor level
Travel time estimation	Weighted mean of several travel-time estimators. Weights are a function of the variance or covariance of the estimators.	Sensor level
Travel time estimation	Weighted mean where the weights are a function of the data source reliability.	Sensor level
Travel time estimation	Fuzzy logic	Sensor level
Vehicle and object tracking	Kalman filter	Central level
Lane departure warning	Image processing using edge detection and extraction of other features.	Pixel level
Traffic state estimation	Extended Kalman filter	Central level
Crash analysis and prevention	*k*-means algorithm	Sensor level or decision level
Traffic forecasting and monitoring	Bayesian inference	Sensor level
Traffic forecasting and monitoring	Artificial neural network	Sensor level
Traffic forecasting and monitoring	Kalman filter	Central level
Traffic forecasting and monitoring	Extended Kalman filter	Central level
Traffic forecasting and monitoring	Kernel estimator	Central level
Traffic forecasting and monitoring	Particle filter	Central level
Vehicle position estimation	Unscented Kalman filter	Central level
Vehicle position estimation	Artificial neural network	Central level

Data fusion techniques applied to date as shown in include Bayesian inference, Dempster-Shafer evidential reasoning, artificial neural networks, fuzzy logic, and Kalman filtering. Adetiloye and Awasthi (2019) proposed a multimodal big data fusion framework for traffic congestion prediction using the City of Montreal. It involves distributed traffic data fusion architecture with homogenous (quantitative only) and heterogeneous (quantitative, qualitative) data. The homogeneous data fusion model fuses data of same types (quantitative) estimated using machine-learning algorithms: back propagation neural network (NN), random forest (RF), and deep belief network (DBN); and applies extended Kalman filter (EKF) for the stochastic filtering of the non-linear noisiness while reducing the estimation and measurement errors. In the heterogeneous fusion model, the homogenous model was extended by integrating with qualitative data, i.e., traffic tweet information from Twitter data source. The results of the extended Kalman filter and sentiment analysis are treated using the Mamdani Fuzzy Rule Inferencing (MFRI) for heterogeneous traffic data fusion (Adetiloye and Awasthi, 2019).

The results emphasize the improvements made in the prediction of travel times using traffic big data of vehicles' traversing various road network nodes in the city of Montreal. The model validation was accomplished with the Genetec blufaxcloud travel-time system engine (GBTTSE). The strength of proposed work was the use of big data fusion for traffic congestion prediction in near real-time situation based on the traffic travel times of road vehicles on urban motorways. The limitation was lack of adequate system tools to seamlessly integrate data from various sources for real-time traffic information. As future work, one could also consider the use of traffic image, video, and other real-time data to improve traffic congestion prediction while integrating them to our existing framework. Secondly, the study can be extended by integrating various geographical contexts, connected locations, merges, ramps, etc. (Adetiloye and Awasthi, 2019).

Shi et al. (2017) also investigated a heterogeneous data fusion method travel time distribution. They fused heterogeneous data from point and interval detectors. The three steps they used to achieve results are summarized in the following bullets.

- The first step, i.e., data preprocessing, was designed to respectively estimate path travel time distributions from interval and point detector data. The spatially missing data issue of point detectors was addressed. The travel time distributions of links without point detectors were imputed based on their spatial correlations with links that had point detectors.
- The second step, i.e., distribution fusion, fused these two path travel time distributions estimated from interval and point detectors. A D-S distribution fusion algorithm built on the Dempster-Shafer evidence theory was proposed to fuse path travel time distributions from different data sources with various information qualities.
- The third step, i.e., posterior update, updated link travel time distributions and their spatial correlations. The problem of updating spatial correlations was formulated and solved as a quadratic programming problem with a convex objective function and two linear constraints.

A case study was performed using real-world data from Hong Kong and showed that the proposed method obtained accurate and robust estimations of link and path travel time distributions in congested road networks (Shi et al., 2017).

Yang et al. (2020) proposed a data fusion approach to investigate traffic state and identify recurrent bottlenecks quickly and accurately from macroscopic network perspective using data sources from fixed detectors and mobile navigation apps. Their approach used flow-speed fundamental diagram to derive critical speed used as the criterion to determine traffic state. Once the criterion were established, typical bottlenecks in the entire expressway network were efficiently identified through only utilizing smartphone-based probe speed data. Secondly, three pioneering indicators were put forward to quantify oversaturated traffic state and classify bottleneck patterns on urban expressway network. Researchers applied this methodology on a Beijing, China expressway network to identify different patterns of bottlenecks, which were validated to comply with the reality. They explored the relationship between critical speed and the associated road segment features to show the possibility of predicting the critical speed even without flow data (Y. Yang et al., 2020).

Joshi et. al. (2013) demonstrated a fusion-based learning approach to classify the traffic states using low-cost audio and image data analysis using real world dataset. They used roadside collected traffic acoustic signals and traffic image snapshots obtained from fixed camera to classify the traffic condition into three broad classes viz., Jam, Medium and Free. The classification was done on {10sec audio, image snapshot in that 10sec} data tuple. Traffic relevant features from audio (Mel-Frequency Cepstral Coefficients [MFCC] classifier-based features, honk events, and energy peaks) and image data was extracted to form a composite feature vector. A simple heuristic-based image classifier is used, where vehicular density and number of corner points within the road segment are estimated and are used as features for traffic sensing. Finally, the composite vector is tested for its ability to discriminate the traffic classes using decision tree classifier, SVM classifier, discriminant classifier and logistic regression-based classifier. Information fusion at multiple levels (audio, image, overall) shows consistently better performance than individual level decision making. Low-cost sensor fusion based on complementary weak classifiers and noisy features still generates high quality results with an overall accuracy of 93 - 96%.

Wang et al. (2019) developed a prototype artificial intelligence (AI) platform for solving challenging transportation problems using large-volume high-dimensional transportation data and complex models. This AI platform can provide standardized datasets and novel deep learning-based models for solving specific pre-defined transportation problems. Their research conclusions and project contributions are summarized as follows:

- A transportation AI platform incorporating large-volume high-dimensional transportation data and complex models is developed for solving challenging transportation problems. This AI platform can provide standardized datasets and novel deep learning-based models for specific problems.
- A novel architecture is designed for the transportation AI platform to enhance the efficiency of the transportation data processing, management, and communication and increase the computational power of the platform. The transportation AI platform consists of three main components, i.e. the web server, data warehouse, and computation center. All three components are connected by using novel data communication technologies.
- The web server uses a novel web-application framework to provide user-friendly interfaces and support the interaction between users and the platform.
- A data storage and management schema is designed with the help of the data warehouse and the computation center to manage multiple network-wide traffic data sets for supporting the traffic prediction task and to simplify the whole training and testing process.
- Novel deep learning-based traffic prediction models and baseline models are developed and stored in the computation center of the platform. A novel graph-based deep learning, i.e. the graph wavelet gated recurrent (GWGR) network is proposed to capture the complicated topological structure of the roadway network to improve the traffic prediction performance. Compared with baseline models, including LSTM and GRU, the GWGR shows superior prediction performance.
- New visualization technologies are also incorporated in the transportation AI platform to help users intuitively and efficiently use the platform and deploy novel methodologies (Wang et al., 2019).

He et al. (2016) investigated the fusion of a new data combination from cellular handoff probe system and microwave sensors to provide freeway speed estimation. A fusion method based on the neural network technique was proposed, which is illustrated in Figure 12. The locations and time stamps of cellular handoff probe system are processed to extract the space-mean speed. The consistency of handoff location is one of the factors that might affect the estimation accuracy from Cellular Handoff Probe System. Traffic volume is regarded as an influential factor from Microwave Sensors.

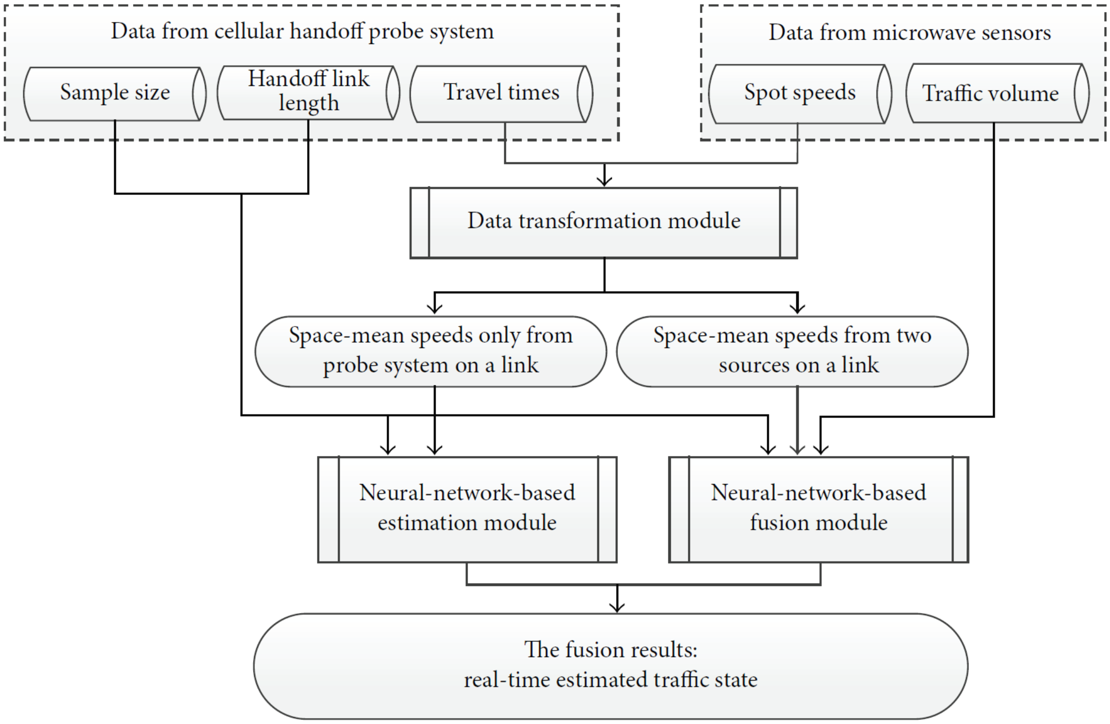


Figure 12. The flowchart of data fusion process (He et al., 2016).

For investigation, the sensitivity of different factors on the accuracy of fusion model was tested by the various combinations of inputs in neural network models. Firstly, the factors of sample size of CHPS, handoff link length, or traffic volume are all influential factors that increase the fusion accuracy. The second finding is that the importance of every influential factor on the fusion accuracy can be inferred. The combination of sample size and handoff link length makes the most influential factor and has more positive impact on the fusion accuracy. Speeds from microwave sensors can achieve high accuracy under free flow condition. However, the error of microwave sensor is high under the incident condition. Sample size and handoff link length are important factors for the improvement of fusion accuracy, which suggests that speed, sample size, and handoff link length should also be the inputs for the neural-network-based estimation module.

Although microwave sensors can provide more accurate estimation under free flow condition, their performance under the congested condition is unstable. Comparatively, the error of CHPS is stable under various traffic conditions which is a little higher than the error of microwave sensors. An analysis of the proposed method and other data fusion approaches shows that the neural-network-based method is optimal. A valid comparison furtherly proved that the proposed method is superior to the convex combination.

Gitahi et. al (2020) use data from INRIX, HERE and TomTom FCD commercial services and fuse the speeds to improve travel time and average segment speeds estimation. Speed differences between each pair of datasets were evaluated by calculating the absolute mean and standard deviation of differences. HERE consistently reports very high values throughout while INRIX shows the highest variance of confidence which is consistent with time-of-day average speeds. The high volume of vehicles during the peak periods improves the probe rate for all the FCD services which results in reduced variations in speed differences. HERE FCD has the lowest spatial resolution with longer segments among the three services and hence the higher variations in speeds when compared to the rest. Generally, the speeds show less variation from each other during peak hours apart from INRIX and HERE pairs where the differences increase.

The MAPE and RMSE scores of INRIX speeds on the main section of the highway against the ground truth speeds, suggest that FCD has the potential to estimate speeds reliably and could be used for real-time congestion-detection and tracking. Long term evaluations of speeds from FCD services against high-quality ground truth data is needed to determine their accuracy and completeness before using the data in traffic management applications. The FCD performance also depends on the location and time of the day and day of the week and consequently there is a need to perform evaluations at the highest possible spatial resolution. Multi-sensor fusion techniques have the potential of increasing the robustness of travel times and mean segment speeds estimation where one source complements lower quality data from another.

Identification of Proactive Management Strategies

As part of this task, the TTI research team assessed different proactive congestion management strategies that have the potential to either delay the onset or mitigate the impact of recurring and nonrecurring congestion on roadway safety and operations. As part of that assessment, the team focused on strategies that can assist in improving an existing congestion management process (CMP) by correlating the planning goals and objectives of the CMP to the proactive management strategies that can help attain those objectives. Many of the strategies selected fit within the broad range of strategies under ATM. Those included in the matrix are shown in Table 6. While this list is not exhaustive in terms of all TSMO strategies that can improve congestion, they have the potential to be utilized in a proactive manner and can incorporate real-time, near real-time, and CAV-related data to enhance their effectiveness.

Table 6. Proactive congestion management strategy descriptions.

Proactive Congestion Management Strategy	Strategy Description
Value Priced Express Toll Lanes	Dedicated lane(s) on a limited access facility where all vehicles are charged a toll to use the lane. Some limited price restrictions or discounts are offered based on vehicle occupancy.
Express Toll Lanes Non-Value Priced	Dedicated lane(s) on a limited access facility where all vehicles are charged a toll to use the lane. Pricing does not vary based on vehicle occupancy.
HOV Lanes	Dedicated lane(s) or facility that gives priority to HOVs (motor vehicles with at least two or more persons, including carpools, vanpools, and buses), including freeway lanes, park & ride lots, and other elements. Individual facilities may require different vehicle occupancy levels, which are expressed typically as either two or more (2+) or three or more (3+) persons per vehicle.
Truck Restricted Lanes	Restrictions requiring trucks to be operated only on two or more designated lanes of a highway. Ensures that at least one of the highway lanes (normally the left or inside lane) is used only by passenger vehicles. A restricted vehicle is allowed to use any lane, including the restricted lane, to pass another vehicle and to enter/exit the highway. Restrictions can be implemented 24 hours a day or just during peak periods.

Proactive Congestion Management Strategy	Strategy Description
Non-tolled Express Lanes	Dedicated lane(s) on a limited access facility that has fewer exits than general purpose lanes. Access can also be restricted to specific users, such as passenger vehicles.
HOT Lanes	The application of pricing to an HOV lane facility to utilize existing capacity. Allows lower occupant vehicles that do not meet occupancy restrictions established for a HOV lane to use it through payment of a toll. Typical HOT projects allow free use to either 2-person (HOV-2) or 3-person (HOV-3) carpools.
Exclusive Transitways	A special roadway designed for the exclusive use of transit vehicles (also known as a busway). Can be in its own right-of-way, or in a railway or highway right-of-way.
Exclusive or Dedicated Truck Lanes	Specific lanes on existing roadways or exclusive facilities or highways that are dedicated for heavy truck use only.
Multifaceted Managed Lanes	Lanes that provide special access to vehicles based on a set of rules, usually occupancy and price.
Dynamic Speed Limits	Use of speed limit signs that can change when roadway sensors detect congestion or adverse weather conditions. Also known as speed harmonization or variable speed limits.
Part-Time Shoulder Use	Permits vehicles to drive on the shoulder of a road, typically at reduced speed limits. May be opened during designated time periods (e.g., peak periods) or the decision to open shoulder use is dynamic, made in the traffic management center based on real-time conditions. May be open for all vehicles or for designated vehicle types such as transit buses, high-occupancy vehicles, or vehicles attending a special event. Also referred to as hard shoulder running or dynamic shoulder use.
Queue Warning	Corridor-level use of signs and flashing lights to tell drivers of upcoming stop-and-go traffic (based on real-time traffic detection). This information can help drivers reduce speed in advance of the traffic.
Adaptive Ramp Metering	The use of signals at entrance ramps to control the number of vehicles entering freeway traffic and makes the merge of vehicles entering the freeway from an entrance ramp smoother. Adaptive system changes the level of control based on traffic.
Dynamic Merge Control	The practice of automatically managing the entry of vehicles into merge areas on a facility. Uses light-up signs to open or close an extra lane based on traffic demand. Can be a useful solution for known bottlenecks or for special events. Also known as dynamic junction control.
Dynamic Truck Restrictions	The use of operational restrictions or financial incentives for freight operators to affect the time, location, and manner in which truck traffic can deliver to certain areas or travel in some corridors.
Dynamic Rerouting and Traveler Information	The availability and provision of truck routing and parking information (freight-specific dynamic travel planning) both pre-trip and en-route to facilitate travel planning, routing, and parking for freight operators.

Proactive Congestion Management Strategy	Strategy Description
Automated Enforcement	The use of technology to automatically enforce usage of facilities (i.e., HOV lanes, HOT lanes, part-time shoulder use, etc.) or operational limitations (i.e., dynamic speed limits, traffic signals, etc.). Not as widely adopted due to privacy concern
Dynamic Lane Reversal	Reversible traffic lanes are a type of traffic management that allows lanes to change direction based on peak congestion times. Implementing this strategy can help reduce congestion during commute times, a lane-blocking accident, special events, and construction. Reversible traffic lanes borrow lanes that typically go in the other direction and are shown through changeable message signs and/or arrows.[21]
Dynamic Lane Use Control	Uses variable message signs to indicate information about specific lanes. The lanes may be opened during specific times of day based on preset arrangements, such as during peak periods. Alternatively, they may be dynamic based on specific needs, such as traffic incident management.

Development of the Decision Matrix

During this task, the TTI research team developed a decision matrix based on goals, objectives, constraints, and other operational conditions and preferences for use by infrastructure owner operators with which they can select potential operational strategies to consider for implementation to work toward proactive congestion management. The matrix is intended to complement the simulation models of strategies developed by University of South Florida and to provide specific guidance and recommendations that will benefit agencies in the rapid deployment of strategies in response to potential field condition triggers. The TTI team coordinated with the USF research team to incorporate data elements that emerged from their simulation models that could be used in the proactive selection of strategies to help mitigate congestion.

Decision Matrix Structure

The TTI team developed a draft matrix structure based on an active management screening tool (AMST) that was developed previously. The purpose of the AMST was to help agencies better assess the potential of active management strategies for their region. It was structured to provide beneficial information and guidance related to active management strategies. It was also intended to directly link the transportation planning process with operations by providing regions with information on which operational strategies they might include in the regional transportation plan that have the potential to provide the most benefit to the regional transportation network (Kuhn et al, 2011).

The AMST provides, at a screening level, major attributes about candidate corridors that and agency can use to help determine if any active management strategy is suitable and appropriate. It also determines in successive steps which strategy and its companion support facility and program needs best respond to the mobility, safety, and environmental needs of the corridor. The active management strategies included in the original AMST were as follows:

- high occupancy vehicle lanes;
- high occupancy toll lanes;
- express tolled and non-tolled lanes;

- exclusive/dedicated truck lanes;
- exclusive transitways;
- temporary shoulder use;
- speed harmonization;
- queue warning;
- dynamic rerouting and traveler information;
- ramp metering;
- dynamic merge control; and
- automated enforcement.

Given the similarities between the original AMST and the overall intent of the proactive congestion management matrix, the TTI team used the original structure of the AMST as a launching point to optimize resources. The project team expanded the proactive congestion management strategies included in the new matrix to match those noted previously and developed content around the following critical elements:

- active management goals;
- active management objectives;
- active management performance measures;
- implementation constraints;
- enabling infrastructure and technologies;
- cost considerations (core elements, operations, maintenance)
- application geography;
- compatible strategies; and
- potential benefits.

The TTI Team then refined the structure of the Proactive Congestion Management Strategy Framework (PCMSF) around these elements to ensure the relationships between the proactive congestion management strategies and the elements were accurately and fully represented. Figure 13 illustrates the structure of the matrix and the relationships between the related elements. All the individual relationship tables provided in the matrix are included in Appendix A.

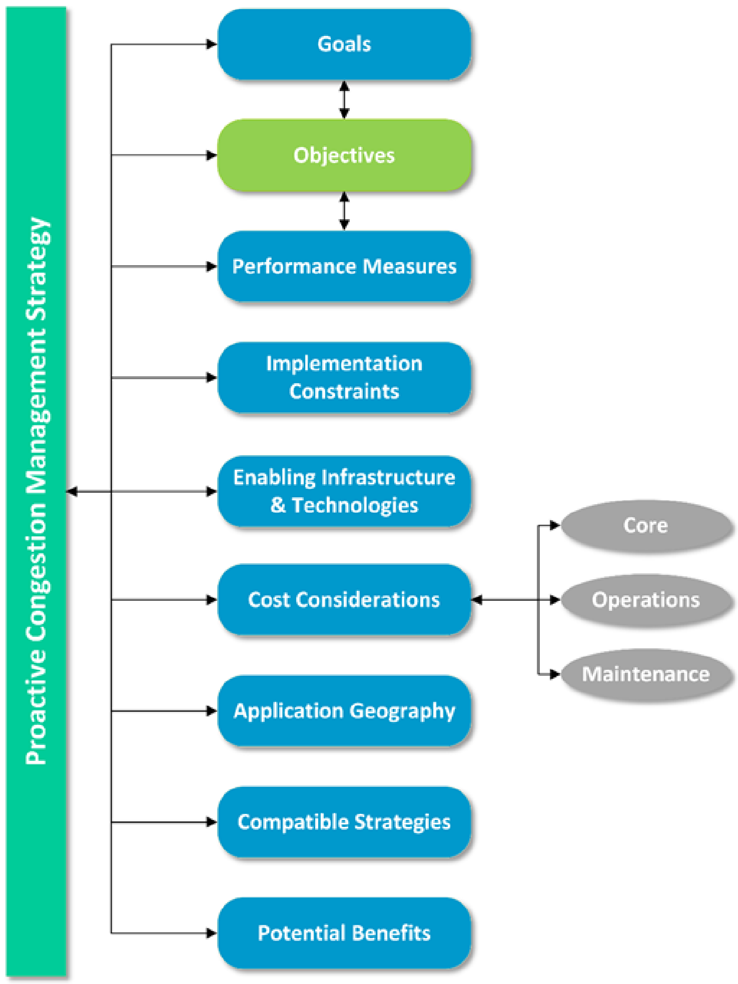


Figure 13. Structure of proactive congestion management decision matrix.

Online Screening Tool

The TTI team converted the proactive congestion management decision matrix into an online screening tool that offers users an easy approach to selecting potential operational strategies based on their preferred or anticipated active management objectives. The tool was developed using an online decision tree platform and is currently housed online at the following URL: https://zingtree.com/show/203440350000. Figure 14 illustrates the 2-step process to use the tool. Initially, the user selects a preferred active management objective from a list of options (see Figure 15). Once a user selects an objective, the user then selects an active management operational strategy for possible deployment (see Figure 16). Upon strategy selection, the tool generates a detailed output that includes the critical information included in the matrix (see Figure 17 and Figure 18). The tool is easy to restart or revise to select various options. The user can print the results and make comparisons as desired to determine what strategies might be viable for their jurisdiction.

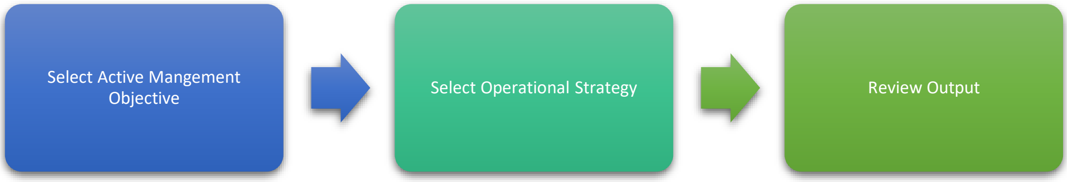


Figure 14. Proactive Congestion Management Strategy Framework selection process.

Figure 15. Active management objective selection screen, Proactive Congestion Management Strategy Framework Tool.

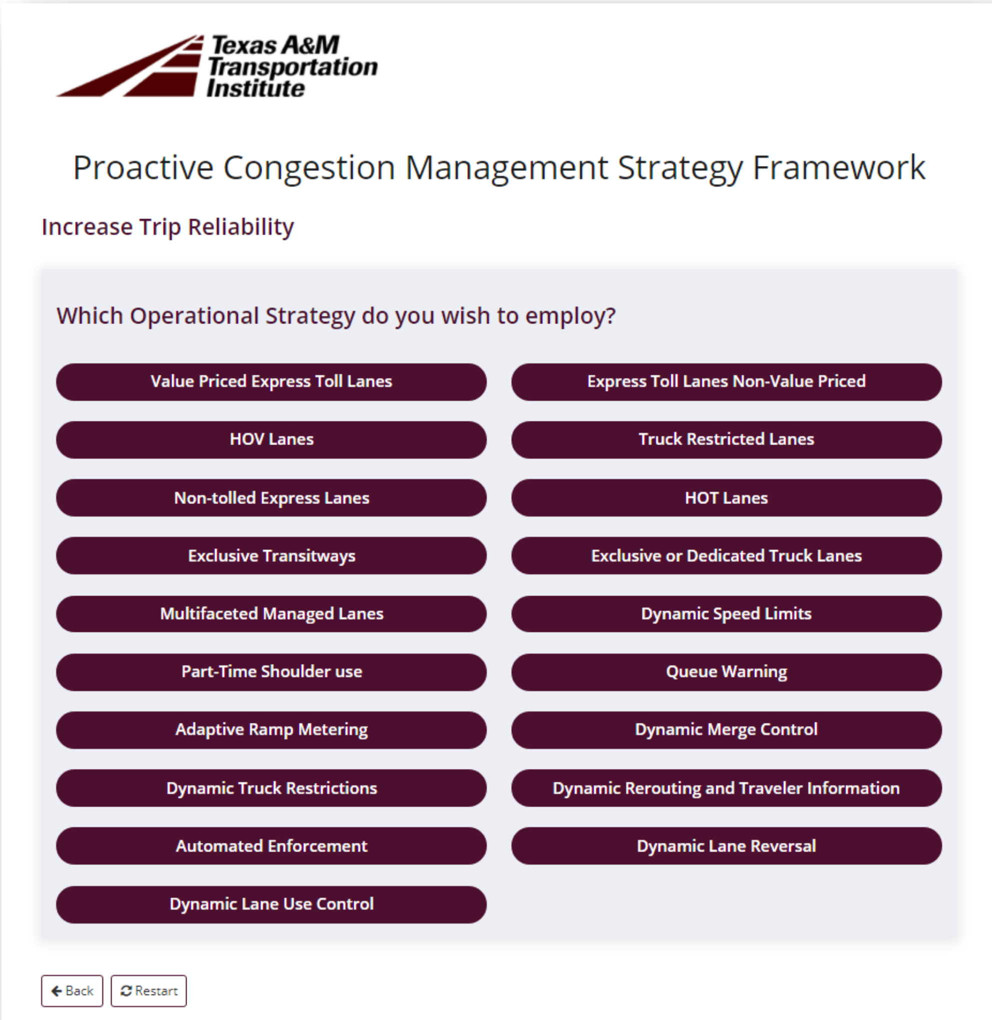


Figure 16. Operational strategy selection screen, Proactive Congestion Management Strategy Framework Tool.

Texas A&M Transportation Institute

Proactive Congestion Management Strategy Framework

Dynamic Speed Limits

Description

Use of speed limit signs that can change when roadway sensors detect congestion or adverse weather conditions. Also known as speed harmonization or variable speed limits.

Applicable Goals

Provide a Reliable Alternative
Optimize Existing Capacity
Improve Congested Roadways
Improve the Safety of Corridor Travel
Maintain Level of Safety on a Facility
Minimize Environmental Impacts

Anticipated Benefits

Delayed Onset of Main Lane Breakdown
Improved Level of Service
Reduced Main Lane Travel Delay
Increased On-Time Arrival
Reduced Speed Variability
Reduced Speed Differential
Improved Travel Time Reliability
Reduced Vehicle Hours Traveled
Reduced Travel Delay
Reduced Crash Rates
Reduced Crash Severity
Reduced Spatial Extent of Congestion

Applicable Roadway Areas

Freeway / Arterial

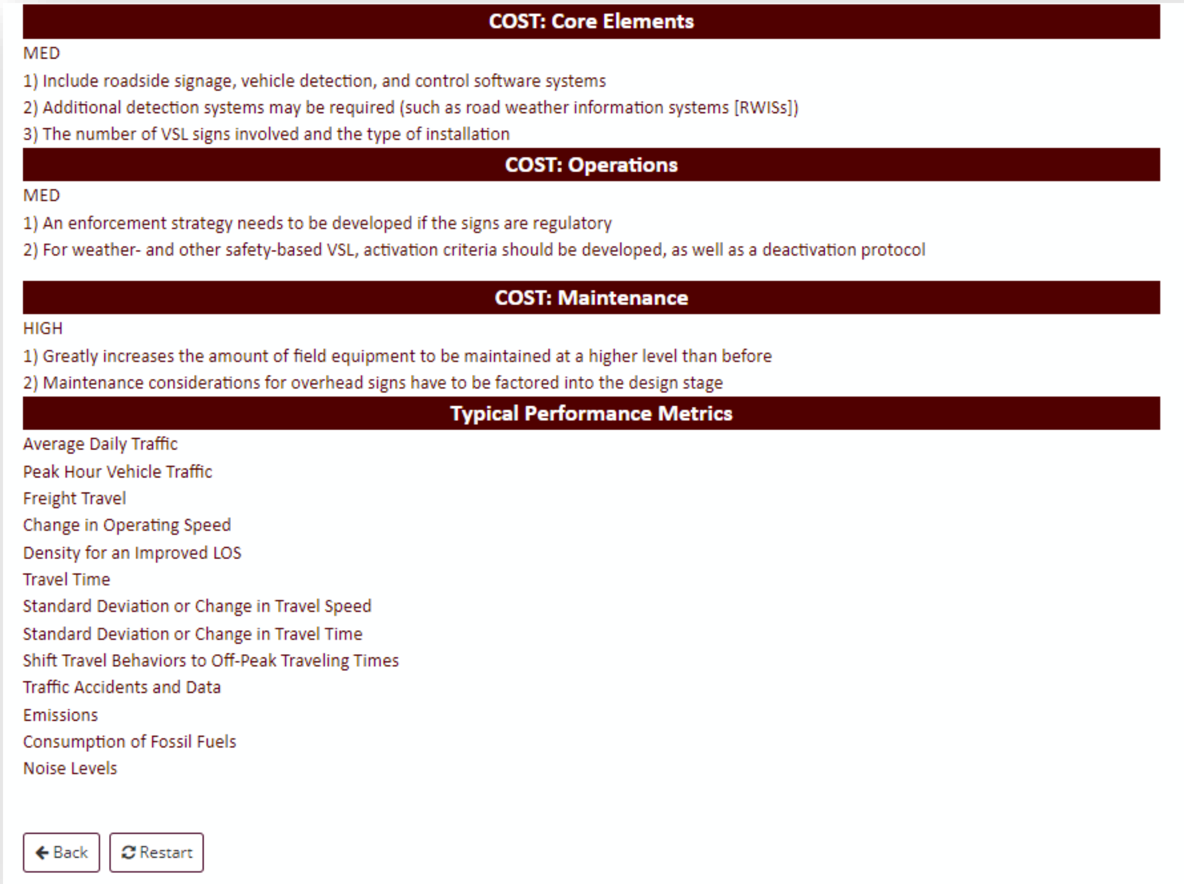
Enabling Technologies

INFRASTRUCTURE
Static Roadside Signage
Dynamic Roadside Signage (PCMS, Speed Feedback, etc.)
Dynamic On-Road Signage (DMS, Lane Control Signals, etc.)
Vehicle Detection
Automatic License Plate Recognition (ALPR)

SYSTEMS
Control Software Systems
Incident Detection Systems
Traveler Information Systems
In-Vehicle Alert Systems
Positioning Systems (GPS)
Communications (Bluetooth, WiFi, Cellular, DSRC, etc.)

DATA
Real-Time Connected Vehicle Data Stream
Real-Time Telematics Connected Vehicle Data Stream
Real-Time Autonomous Vehicle Data Stream

Figure 17. Dynamic speed limits output, Proactive Congestion Management Strategy Framework.



COST: Core Elements

MED

1) Include roadside signage, vehicle detection, and control software systems
2) Additional detection systems may be required (such as road weather information systems [RWISs])
3) The number of VSL signs involved and the type of installation

COST: Operations

MED

1) An enforcement strategy needs to be developed if the signs are regulatory
2) For weather- and other safety-based VSL, activation criteria should be developed, as well as a deactivation protocol

COST: Maintenance

HIGH

1) Greatly increases the amount of field equipment to be maintained at a higher level than before
2) Maintenance considerations for overhead signs have to be factored into the design stage

Typical Performance Metrics

Average Daily Traffic
Peak Hour Vehicle Traffic
Freight Travel
Change in Operating Speed
Density for an Improved LOS
Travel Time
Standard Deviation or Change in Travel Speed
Standard Deviation or Change in Travel Time
Shift Travel Behaviors to Off-Peak Traveling Times
Traffic Accidents and Data
Emissions
Consumption of Fossil Fuels
Noise Levels

Back
Restart

Figure 18. Dynamic speed limits output, Proactive Congestion Management Strategy Framework (continued).

Dissemination of Research Results

The TTI team prepared and delivered a webinar (see Figure 19) targeted at infrastructure owner-operators to introduce the decision matrix and demonstrate its use for operational strategy decision-making using the online screening tool. The TTI team has prepared documentation for the research project and plans to develop research articles for delivery to target audiences via conferences and peer-reviewed journals. The final version of the online screening tool and related matrix will be made available online for ready access by practitioners. Social media outreach will also be developed to ensure the broad dissemination of the research results.

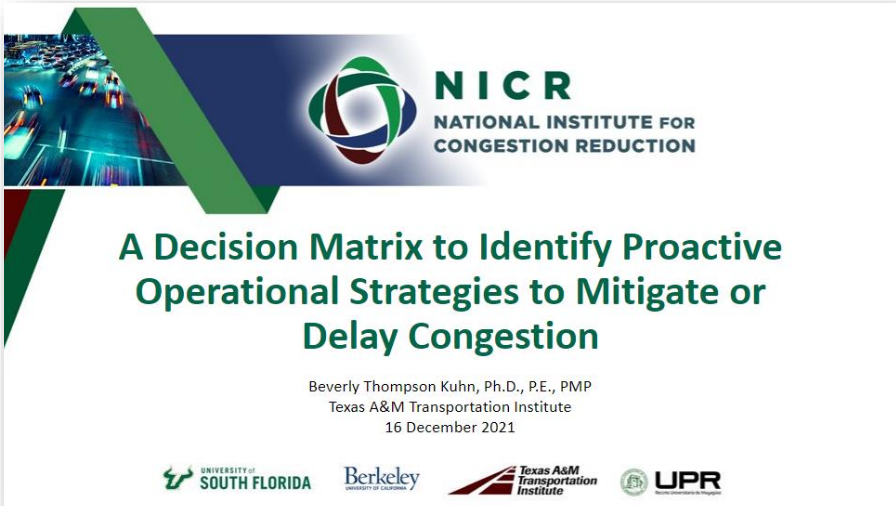


Figure 19. TTI webinar and demonstration of the proactive congestion management strategy framework.

Final Remarks

It is the hope of the authors that by providing transportation agencies with a readily available and easy-to-use tool and matrix to screen for proactive congestion management operational strategies can have a positive impact on transportation networks where these strategies are feasible. Potential transportation improvements can include an increase in average throughput for congested periods, an increase in overall capacity, a decrease in primary accidents, a decrease in secondary accidents, a decrease in accident severity, an overall harmonization of speeds during congested periods, an increase in trip reliability, and the ability to delay the onset of freeway breakdown. Proactive congestion management has the potential to help transportation agencies address the ever-increasing challenge of doing more with less and operating existing facilities in the most efficient manner possible.

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Appendix A. Proactive Congestion Management Strategy Framework Tables

Active Management Operational Strategies	Active Management Goals							
	Provide a Reliable Alternative	Provide a Transportation System that Can Handle Current and Future Demand	Increase Mobility and Accessibility by Offering Travel Options	Provide Additional Facility Capacity	Optimize Existing Capacity	Optimize Existing Managed Lanes Capacity	Improve Congested Roadways	Modify Travel Demand
Value Priced Express Toll Lanes	X	X	X	X	X	X	X	X
Express Toll Lanes Non-Value Priced	X	X	X	X		X	X	X
HOV Lanes	X	X	X	X		X	X	X
Truck Restricted Lanes	X	X	X	X		X	X	X
Non-tolled Express Lanes		X	X	X		X	X	X
HOT Lanes	X	X	X	X	X	X	X	X
Exclusive Transitways	X	X	X	X		X	X	X
Exclusive or Dedicated Truck Lanes	X	X	X	X		X	X	X
Multifaceted Managed Lanes	X	X	X	X	X	X	X	X
Dynamic Speed Limits	X				X		X	
Part-Time Shoulder Use	X	X	X	X	X		X	
Queue Warning	X				X		X	
Adaptive Ramp Metering	X	X	X		X		X	
Dynamic Merge Control	X	X	X		X		X	
Dynamic Truck Restrictions	X	X	X	X	X		X	
Dynamic Rerouting and Traveler Information	X	X	X	X	X		X	
Automated Enforcement	X				X			
Dynamic Lane Reversal	X	X	X	X	X		X	
Dynamic Lane Use Control	X	X	X		X		X	

Figure 20. Active management operational strategies vs. active management goals.

Active Management Operational Strategies	Active Management Goals								
	Enhance Alternative Modes of Travel	Improve Accessibility	Improve the Safety of Corridor Travel	Maintain Level of Safety on a Facility	Minimize Environmental Impacts	Preserve Neighborhoods	Maintain Land Use Patterns	Develop Transportation Improvements that Help Offset Costs	Maximize the Benefit-Cost Ratio of Infrastructure Invesement
Value Priced Express Toll Lanes	X			X	X			X	X
Express Toll Lanes Non-Value Priced	X			X				X	X
HOV Lanes	X	X	X	X	X	X	X		
Truck Restricted Lanes			X	X	X	X	X		
Non-tolled Express Lanes				X					
HOT Lanes	X	X		X	X	X	X	X	X
Exclusive Transitways	X	X	X	X	X	X	X		
Exclusive or Dedicated Truck Lanes		X	X	X	X	X	X		
Multifaceted Managed Lanes	X	X	X	X	X	X	X	X	X
Dynamic Speed Limits			X	X	X				
Part-Time Shoulder Use		X	X	X					
Queue Warning			X	X	X				
Adaptive Ramp Metering		X	X	X	X				
Dynamic Merge Control		X	X	X	X				
Dynamic Truck Restrictions		X	X	X	X				
Dynamic Rerouting and Traveler Information	X	X	X	X	X				
Automated Enforcement			X	X					
Dynamic Lane Reversal		X	X	X	X				
Dynamic Lane Use Control		X	X	X	X				

Figure 21. Active management operational strategies vs. active management goals (continued).

Active Management Goals	Active Management Objectives													
	Increase Vehicle-Carrying Capacity	Increase Person-Carrying Capacity	Increase Goods-Carrying Capacity	Maintain Free Flow Speed	Maintain or Improve Level of Service	Reduce Travel Time	Increase Trip Reliability	Provide Travel Alternatives	Reduce Peak Period Vehicle Trips	Improve Express Bus Service	Provide Transmodal Connectivity and Accessibility	Minimize Traffic Crashes Involving Large Trucks	Minimize Primary Traffic Crashes	Reduce Incident Severity
Provide a Reliable Alternative	X	X	X	X	X	X	X	X	X	X	X	X	X	
Provide a Transportation System that Can Handle Current and Future Demand	X	X	X	X	X	X	X	X	X	X	X	X	X	
Increase Mobility and Accessibility by Offering Travel Options	X	X		X	X	X	X	X	X	X	X			
Provide Additional Facility Capacity	X		X		X		X	X				X	X	
Optimize Existing Capacity		X	X		X	X	X	X	X	X	X			
Optimize Existing Managed Lanes Capacity		X	X	X	X	X	X	X	X	X	X			
Improve Congested Roadways	X	X	X		X	X	X	X	X	X	X	X	X	X
Modify Travel Demand		X	X				X	X	X	X	X			
Enhance Alternative Modes of Travel		X		X	X		X	X	X	X	X			
Improve Accessibility	X	X	X		X	X	X	X	X	X	X			
Improve the Safety of Corridor Travel							X	X	X	X		X	X	X
Maintain Level of Safety on a Facility							X	X	X	X		X	X	X
Minimize Environmental Impacts		X		X	X	X		X	X	X	X	X	X	X
Preserve Neighborhoods		X	X		X		X	X	X	X	X			
Maintain Land Use Patterns		X	X		X		X	X	X	X	X			
Develop Transportation Improvements that Help Offset Costs														
Maximize the Benefit-Cost Ratio of Infrastructure Invesement														

Figure 22 Active management goals vs. active management objectives.

Active Management Goals	Active Management Objectives													
	Minimize Secondary Crashes	Improve Air Quality from Mobile Sources	Reduction in Fuel Consumption	Address Environmental Justice Concerns	Encourage Transit Oriented Development	Fund New Transit and Managed Lanes Improvements	Produce Enough Revenue to Cover O/M and Enforcement	Produce Enough Revenue to Cover Debt Service	Private Investment Profit	Generate More Uniform Speeds in Travel Lanes	Decrease Headways between Vehicles	Promote More Uniform Driver Behavior	Delay Onset of Freeway Breakdown	Reduce Traffic Noise
Provide a Reliable Alternative	X				X					X	X	X	X	
Provide a Transportation System that Can Handle Current and Future Demand	X	X	X		X					X	X	X	X	X
Increase Mobility and Accessibility by Offering Travel Options				X	X					X	X	X	X	
Provide Additional Facility Capacity	X	X	X	X	X					X	X	X	X	X
Optimize Existing Capacity		X	X	X	X					X	X	X	X	
Optimize Existing Managed Lanes Capacity		X	X	X	X	X	X	X	X					
Improve Congested Roadways	X	X	X	X	X					X	X	X	X	X
Modify Travel Demand		X	X	X	X	X								
Enhance Alternative Modes of Travel		X	X	X	X									X
Improve Accessibility				X	X									
Improve the Safety of Corridor Travel	X									X	X	X	X	
Maintain Level of Safety on a Facility	X									X	X	X	X	
Minimize Environmental Impacts	X	X	X	X	X	X				X			X	X
Preserve Neighborhoods				X	X								X	X
Maintain Land Use Patterns				X	X								X	X
Develop Transportation Improvements that Help Offset Costs						X	X	X	X					
Maximize the Benefit-Cost Ratio of Infrastructure Invesement						X	X	X	X					

Figure 23. Active management goals vs. active management objectives (continued).

Active Management Operational Strategies	Active Management Objectives																															
	Increase Vehicle-Carrying Capacity	Increase Person-Carrying Capacity	Increase Goods-Carrying Capacity	Maintain Free Flow Speed	Maintain or Improve Level of Service	Reduce Travel Time	Increase Trip Reliability	Provide Travel Alternatives	Reduce Peak Period Vehicle Trips	Improve Express Bus Service	Provide Transmodal Connectivity and Accessibility	Minimize Traffic Crashes Involving Large Trucks	Minimize Primary Traffic Crashes	Reduce Incident Severity	Minimize Secondary Crashes	Improve Air Quality from Mobile Sources	Reduction in Fuel Consumption	Address Environmental Justice Concerns	Encourage Transit Oriented Development	Fund New Transit and Managed Lanes Improvements	Produce Enough Revenue to Cover O/M and Enforcement	Produce Enough Revenue to Cover Debt Service	Private Investment Profit	Provide Priority to HOV/HOT, Transit, or Other Modal Applications at Ramps	Provide Dedicated Merge Access for HOV/HOT or Transit Applications	Provide Dedicated Shoulders for HOV/HOT or Transit Applications	Provide Higher Speed Limits for Preferential Vehicles	Generate More Uniform Speeds in Travel Lanes	Decrease Headways between Vehicles	Promote More Uniform Driver Behavior	Delay Onset of Freeway Breakdown	Reduce Traffic Noise
Value Priced Express Toll Lanes	X			X		X	X	X	X				X							X	X	X	X									
Express Toll Lanes Non-Value Priced	X			X		X	X	X					X							X	X	X	X									
HOV Lanes	X	X		X	X	X	X	X	X	X			X			X	X	X	X													
Truck Restricted Lanes	X		X	X	X	X	X	X	X	X		X	X					X														
Non-tolled Express Lanes	X					X	X						X																			
HOT Lanes	X	X		X		X	X	X	X	X			X			X	X	X	X	X	X	X	X									
Exclusive Transitways	X	X		X		X	X	X	X	X	X		X			X	X	X	X													
Exclusive or Dedicated Truck Lanes	X		X	X		X	X	X	X	X	X	X	X			X	X	X														
Multifaceted Managed Lanes	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X									
Dynamic Speed Limits	X		X	X	X	X	X						X	X	X	X	X										X	X	X	X	X	X
Part-Time Shoulder Use	X		X	X	X	X	X			X			X		X		X									X		X			X	
Queue Warning	X		X			X	X						X	X	X	X	X											X	X	X	X	X
Adaptive Ramp Metering	X		X	X	X	X	X			X	X		X	X	X	X	X	X	X					X				X	X	X	X	X
Dynamic Merge Control				X	X	X	X			X			X		X	X	X								X			X		X	X	X
Dynamic Truck Restrictions	X		X		X	X	X					X	X	X	X	X	X											X			X	X
Dynamic Rerouting and Traveler Information			X		X	X	X								X	X	X														X	
Automated Enforcement					X		X						X		X													X	X	X		
Dynamic Lane Reversal	X		X		X	X	X						X		X	X	X											X	X		X	X
Dynamic Lane Use Control				X	X	X	X						X		X	X	X											X	X	X	X	X

Figure 24. Active management operational strategies vs. active management objectives.

Active Management Objectives	Active Management Performance Measures																							
	Average Daily Traffic	Peak Hour Vehicle Traffic	Persons/Hour During Peak	Vehicle Occupancy Rate	Formation of HOV Groups	Bus Ridership	Persons/Hour of Total Freeway	Freight Travel	Change in Operating Speed	Density for an Improved LOS	Travel Time	Standard Deviation or Change in Travel Speed	Standard Deviation or Change in Travel Time	Shift Travel Behaviors to Off-Peak Traveling Times	Bus Efficiency	Bus Safety	Impacts to Neighborhood Acces s and Circulation	Traffic Accidents Involving Trucks	Traffic Accidents and Data	Emissions	Consumption of Fossil Fuels	Noise Levels	Impacts to Residences and Businesses	Revenue Generated by Tolling	Accelerated Construction and Implementation
Increase Vehicle-Carrying Capacity	X	X	X																						
Increase Person-Carrying Capacity			X	X	X	X	X																		
Increase Goods-Carrying Capacity								X																	
Maintain Free Flow Speed									X																
Maintain or Improve Level of Service										X															
Reduce Travel Time											X														
Increase Trip Reliability												X	X												
Provide Travel Alternatives					X	X																			
Reduce Peak Period Vehicle Trips														X											
Improve Express Bus Service						X									X	X									
Provide Transmodal Connectivity and Accessibility					X	X											X								
Minimize Traffic Crashes Involving Large Trucks																		X							
Minimize Primary Traffic Crashes																			X						
Reduce Incident Severity																			X						
Minimize Secondary Crashes																			X						
Improve Air Quality from Mobile Sources																				X	X				
Reduction in Fuel Consumption																					X				
Address Environmental Justice Concerns																	X						X		
Encourage Transit Oriented Development					X	X											X						X		
Fund New Transit and Managed Lanes Improvements																								X	X
Produce Enough Revenue to Cover O/M and Enforcement																								X	X
Produce Enough Revenue to Cover Debt Service																								X	X
Private Investment Profit																								X	X
Generate More Uniform Speeds in Travel Lanes									X		X	X													
Decrease Headways between Vehicles										X															
Promote More Uniform Driver Behavior										X		X	X												
Delay Onset of Freeway Breakdown		X							X	X	X			X											
Reduce Traffic Noise																						X			

Figure 25. Active management objectives vs. active management performance measures.

Active Management Operational Strategies	Active Management Performance Measures																								
	Average Daily Traffic	Peak Hour Vehicle Traffic	Persons/Hour During Peak	Vehicle Occupancy Rate	Formation of HOV Groups	Bus Ridership	Persons/Hour of Total Freeway	Freight Travel	Change in Operating Speed	Density for an Improved LOS	Travel Time	Standard Deviation or Change in Travel Speed	Standard Deviation or Change in Travel Time	Shift Travel Behaviors to Off-Peak Traveling Times	Bus Efficiency	Bus Safety	Impacts to Neighborhood Acces s and Circulation	Traffic Accidents Involving Trucks	Traffic Accidents and Data	Emissions	Consumption of Fossil Fuels	Noise Levels	Impacts to Residences and Businesses	Revenue Generated by Tolling	Accelerated Construction and Implementation
Value Priced Express Toll Lanes	X	X	X						X		X	X	X	X					X					X	X
Express Toll Lanes Non-Value Priced	X	X	X						X		X	X	X						X					X	X
HOV Lanes	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X		X	X	X		X		
Truck Restricted Lanes	X	X	X					X	X	X	X	X	X	X	X	X	X	X	X				X		
Non-tolled Express Lanes	X	X	X								X	X	X						X						
HOT Lanes	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X		X	X	X		X	X	X
Exclusive Transitways	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X		X	X	X		X		
Exclusive or Dedicated Truck Lanes	X	X	X					X	X		X	X	X	X	X	X	X	X	X	X	X		X		
Multifaceted Managed Lanes	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X
Dynamic Speed Limits	X	X	X					X	X	X	X	X	X	X					X	X	X	X			
Part-Time Shoulder Use	X	X	X			X		X	X	X	X	X	X	X	X	X			X		X				
Queue Warning	X	X	X					X	X	X	X	X	X	X					X	X	X	X			
Adaptive Ramp Metering	X	X	X			X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X		
Dynamic Merge Control		X				X			X	X	X	X	X	X	X	X			X	X	X	X			
Dynamic Truck Restrictions	X	X	X					X	X	X	X	X	X	X				X	X	X	X	X			
Dynamic Rerouting and Traveler Information		X						X	X	X	X	X	X	X					X	X	X				
Automated Enforcement									X	X	X	X	X						X						
Dynamic Lane Reversal	X	X	X					X	X	X	X	X	X	X					X	X	X	X			
Dynamic Lane Use Control		X							X	X	X	X	X	X					X	X	X	X			

Figure 26. Active management operational strategies vs. active management performance measures.

Active Management Operational Strategies	Implementation Constraints																										
	ROW Available to Add Additional Lane			Currently HOV Lanes in Other Corridors			Percentage of Accidents Caused by Trucks			Route Currently a HAZMAT Route		Length of Proposed Managed Lane			Available Initial Capital			Percentage of Peak Period Traffic That is Freight			Available O&M Funds/Year			Driver Type		
	Unknown	<18'*	>18'*	Unknown	Yes	No	Unknown	<20%	>20%	Yes	No	Unknown	<7 mi	>7 mi	Unknown	<$500,000/mi	>$500,000/mi	Unknown	<20%	>20%	Unknown	<$100,000/mi	>$100,000/mi	Unknown	Residents	People During Through
Value Priced Express Toll Lanes			x		x								x	x			x					x			x	
Express Toll Lanes Non-Value Priced			x		x								x	x			x					x	x		x	
HOV Lanes			x		x								x	x			x					x			x	x
Truck Restricted Lanes		x								x				x		x						x				x
Non-tolled Express Lanes			x		x								x	x			x					x			x	x
HOT Lanes			x		x								x	x			x					x			x	
Exclusive Transitways			x		x								x	x			x					x	x		x	
Exclusive or Dedicated Truck Lanes			x							x				x			x				x					x
Multifaceted Managed Lanes			x		x								x	x			x					x	x		x	x
Dynamic Speed Limits																										
Part-Time Shoulder Use																										
Queue Warning																										
Adaptive Ramp Metering																										
Dynamic Merge Control																										
Dynamic Truck Restrictions																										
Dynamic Rerouting and Traveler Information																										
Automated Enforcement																										
Dynamic Lane Reversal																										
Dynamic Lane Use Control																										

Figure 27. Active management operational strategies vs. implementation constraints.

Active Management Operational Strategies	Implementation Constraints																																
	Types of Trucks That Use Roadway			Route Serves Major Activity Center			Congestion Index for Roadway in Question			Median Family Income in Corridor			Vehicles Per Household in Corridor			Another Form of Mass Transit in City			Number of Buses that will Use Managed Lane Daily			Truck Restrictions Currently in City			Corridor is Currently a Trucking Route			Political Opposition to Toll Roads in City			Alternative Truck Routes Nearby		
	Unknown	Light-Duty	Freight 3+ axle	Unknown	Yes	No	Unknown	< 1.0	> 1.0	Unknown	<$30,000	>$30,000	Unknown	<1/hh	>1/hh	Unknown	Yes	No	Unknown	<100	>100	Unknown	Yes	No	Unknown	Yes	No	Unknown	Yes	No	Unknown	Yes	No
Value Priced Express Toll Lanes		x			x				x	x										x										x			
Express Toll Lanes Non-Value Priced		x			x				x	x										x									x				
HOV Lanes					x				x	x										x	x								x				
Truck Restricted Lanes		x	x	x						x													x			x						x	
Non-tolled Express Lanes		x			x				x	x										x	x								x				
HOT Lanes					x				x	x											x									x			
Exclusive Transitways					x				x	x										x	x												
Exclusive or Dedicated Truck Lanes		x	x	x						x													x			x						x	
Multifaceted Managed Lanes	x	x			x				x	x										x								x					
Dynamic Speed Limits																																	
Part-Time Shoulder Use																																	
Queue Warning																																	
Adaptive Ramp Metering																																	
Dynamic Merge Control																																	
Dynamic Truck Restrictions			x																				x			x						x	
Dynamic Rerouting and Traveler Information																																	
Automated Enforcement																																	
Dynamic Lane Reversal																																	
Dynamic Lane Use Control																																	

Figure 28. Active management operational strategies vs. implementation constraints (continued).

	Enabling Infrastructure & Technologies								
	Infrastructure								
	Static Roadside Signage	Dynamic roadside Signage (PCMS, Speed Feedback, etc.)	Dynamic on-road signage (DMS, Lane Control Signals, etc.)	Traffic Signal Hardware	Access Control Systems	Intrusion Detection Systems	Vehicle Detection	Road Weather Information Systems (RWIS)	Automatic License Plate Recognition (ALPR)
Value Priced Express Toll Lanes	X	X	X		X	X	X	X	X
Express Toll Lanes Non-Value Priced	X	X	X		X	X	X	X	X
HOV Lanes	X		X		X	X	X	X	X
Truck Restricted Lanes	X	X	X		X	X	X	X	X
Non-tolled Express Lanes	X	X	X		X	X	X	X	X
HOT Lanes	X	X	X		X	X	X	X	X
Exclusive Transitways	X		X		X	X	X	X	X
Exclusive or Dedicated Truck Lanes	X	X	X		X	X	X	X	X
Multifaceted Managed Lanes	X	X	X		X	X	X	X	X
Dynamic Speed Limits	X	X	X				X		X
Part-Time Shoulder Use	X	X	X		X	X	X		
Queue Warning	X	X	X			X	X		
Adaptive Ramp Metering	X		X	X	X	X	X		
Dynamic Merge Control	X	X	X		X	X	X		
Dynamic Truck Restrictions	X	X	X		X	X	X		
Dynamic Rerouting and Traveler Information		X	X				X	X	X
Automated Enforcement	X		X				X		X
Dynamic Lane Reversal	X	X	X		X	X	X		
Dynamic Lane Use Control	X	X	X		X	X	X		

Figure 29. Active management operational strategies vs. enabling infrastructure and technologies.

	Enabling Infrastructure & Technologies								
	Systems						Data		
	Control Software Systems	Incident Detection Systems	Traveler Information Systems	In-Vehicle Alert Systems	Positioning Systems (GPS)	Communications (Bluetooth, WiFi, Cellular, DSRC, etc.)	Real-Time Connected Vehicle Data Stream	Real-Time Telematics Connected Vehicle Data Stream	Real-Time Autonomous Vehicle Data Stream
Value Priced Express Toll Lanes	X	X	X	X	X	X	X	X	X
Express Toll Lanes Non-Value Priced	X	X	X	X	X	X	X	X	X
HOV Lanes	X	X	X	X	X	X	X	X	X
Truck Restricted Lanes	X	X	X	X	X	X	X	X	X
Non-tolled Express Lanes	X	X	X	X	X	X	X	X	X
HOT Lanes	X	X	X	X	X	X	X	X	X
Exclusive Transitways	X	X			X	X	X	X	X
Exclusive or Dedicated Truck Lanes	X	X	X	X	X	X	X	X	X
Multifaceted Managed Lanes	X	X	X	X	X	X	X	X	X
Dynamic Speed Limits	X	X	X	X	X	X	X	X	X
Part-Time Shoulder Use	X	X	X	X	X	X	X	X	X
Queue Warning	X	X		X	X	X	X	X	X
Adaptive Ramp Metering	X			X	X	X	X	X	X
Dynamic Merge Control	X	X		X	X	X	X	X	X
Dynamic Truck Restrictions	X	X		X	X	X	X	X	X
Dynamic Rerouting and Traveler Information	X	X	X	X	X	X	X	X	X
Automated Enforcement	X		X		X	X	X	X	X
Dynamic Lane Reversal	X		X	X	X	X	X	X	X
Dynamic Lane Use Control	X	X	X	X	X	X	X	X	

Figure 30. Active management operational strategies vs. enabling infrastructure and technologies (continued).

Active Management Operational Strategies	Cost Considerations / Core Elements	H	H-M	M	M-L	Low
Value Priced Express Toll Lanes	1) include the facilities that separate managed lanes with general purpose lanes; 2) signal systems and lane controllers	X				
Express Toll Lanes Non-Value Priced	1) include the facilities that separate managed lanes with general purpose lanes; 2) signal systems and lane controllers	X				
HOV Lanes	1) barriers separate HOV lanes and signs for vehicle traveling indication; 2) signal systems and lane controllers; 3) on freeways, facilites seperating roadway, concurrent flow lanes and contraflow lanes are used	X				
Truck Restricted Lanes	1)barriers for trucks restrictions; 2) traffic signs indicate no truck access				X	
Non-tolled Express Lanes	1) barriers separate express lanes; 2)lane access control system			X		
HOT Lanes	1) barriers separate HOT lanes and signs for vehicle traveling indication; 2) signal systems and lane controllers	X				
Exclusive Transitways	1) exclusive lanes for operation and barriers between them and general lanes; 2) facilities in stops for passengers service; 3) information signs on routes and stops	X				
Exclusive or Dedicated Truck Lanes	1) barriers separate truck lanes and existing ones; 2)lane access control system	X				
Multifaceted Managed Lanes	1) highway facilities or lanes that multiple strategies need for inplementation; 2) flexibility maintaining when apply multiple strategies to multi-faceted managed lane	X				
Dynamic Speed Limits	1) include roadside signage, vehicle detection, and control software systems; 2) additional detection systems may be required (such as road weather information systems [RWISs]); 3) the number of VSL signs involved and the type of installation			X		
Part-Time Shoulder Use	1) shoulder conversion to a travel lane will vary based on the original design and width of the roadway facility; 2) noise barriers are another cost item that may be impacted; 3) drainage structures, other geometric design changes, and restriping are often encountered as part of this strategy			X		
Queue Warning	1) costs are minimal if existing field infrastructure like DMSs and detection are located at the right locations along the bottleneck; 2) for work zone and other temporary queue warning applications, cost elements include temporary detection, portable signage, and control systems to monitor, detect, and report on the end of queue				X	
Adaptive Ramp Metering	signal heads, controllers, detectors, signage, ramp metering software; controller upgrades			X		
Dynamic Merge Control	lane control signs mounted on gantries or otherwise on the mainline and the ramps			X		
Dynamic Truck Restrictions	1) facilities and signs to control dynamic lane change; 2) sensors and detection systems to determine whether lanes are now truck restriction or not;	X				
Dynamic Rerouting and Traveler Information	alternative routes along with existing lanes; message and guide signs to inform travelers			X		
Automated Enforcement	1) red lights and cameras for enforcement; 2) signs on the roadsides to regulate drivers' behaviors			X		
Dynamic Lane Reversal	1) for freeway systems, it could include access control systems, wrong-way marking and intrusion detection system, static signage, and improvements to various interchanges and junctions; 2) arterial applications may include a combination of static signage, overhead beacons, lane control signs, and control software	X				
Dynamic Lane Use Control	1) lane control signs and gantries; 2) spacing of these signs influences the cost significantly and may depend on the nature of use	X				

Figure 31. Active management operational strategies vs. cost considerations / core elements.

Active Management Operational Strategies	Cost Considerations / Operations	H	H-M	M	M-L	L
Value Priced Express Toll Lanes	1) facilities that separate managed lanes with general purpose lanes may be repaired if any accidents; 2) signal systems and lane controllers should be in good conditions			X		
Express Toll Lanes Non-Value Priced	1) facilities that separate managed lanes with general purpose lanes may be repaired if any accidents; 2) signal systems and lane controllers should be in good conditions			X		
HOV Lanes	1) signal systems and lane controllers work normally and efficiently; 2) on freeways, facilites seperating roadway, concurrent flow lanes and contraflow lanes should be in good conditions			X		
Truck Restricted Lanes	1)barriers are not destroyed; 2) traffic signs are easily for vision and not polluted				X	
Non-tolled Express Lanes	1) barriers should be in good conditions when in operation; 2)lane access control system			X		
HOT Lanes	1) barriers separate HOT lanes and signs for vehicle traveling indication are in good conditions; 2) signal systems and lane controllers work normally and efficiently			X		
Exclusive Transitways	1) facilities in this system continue working and serving people; 2) information signs on routes and stops provided for customers are accurate and updated;				X	
Exclusive or Dedicated Truck Lanes	keep informing travelers that lanes are only for truck use					X
Multifaceted Managed Lanes	highway facilities or lanes developed and operated normally and incorporate multiple strategies in good combination	X				
Dynamic Speed Limits	1) an enforcement strategy needs to be developed if the signs are regulatory; 2) for weather- and other safety-based VSL, activation criteria should be developed, as well as a deactivation protocol			X		
Part-Time Shoulder Use	1) increased emphasis on incident response may be necessary; 2) drive-through of shoulders to ensure they are clear might be necessary			X		
Queue Warning	1) when implemented with speed harmonization, the queue warning pictograms and/or flashing lights need to be visible to all vehicles; 2) during normal operation, all the signs are blank; the signage should also be consistent and uniform to clearly indicate congestion ahead			X		
Adaptive Ramp Metering	1) similar to regular traffic signal operations; 2) no specific training required					X
Dynamic Merge Control	1) additional incident response might be necessary during operations; 2) automated monitoring of ramp and mainline volumes and activation is optimal			X		
Dynamic Truck Restrictions	1) facilities and signs inform drivers accurately; 2) sensors and detection systems operate in good conditions;					X
Dynamic Rerouting and Traveler Information	1) signs used to inform travelers should keep operating; 2) ensure alternative lanes are in good conditions and ready for use; 3) sensors and sign infrastructue for collecting information are necessary, too			X		
Automated Enforcement	1) red lights and cameras work normally; 2) signs on the roadsides to regulate drivers' behaviors show information correctly			X		
Dynamic Lane Reversal	1) enable emergency personnel to respond to incidents on a facility with limited access; 2) provide for enforcement and tolling if required			X		
Dynamic Lane Use Control	1) dynamic lane use control is typically not an automated activity within a TMC and imposes a significant resource burden on the TMC operators during incidents; 2) adequate resources to monitor and change signage approaches are needed; 3) when used with shoulder lane applications, the ability to monitor the facility for potential obstructions is needed	X				

Figure 32. Active management operational strategies vs. cost considerations / operations.

Active Management Operational Strategies	Cost Considerations / Maintenance	H	H-M	M	M-L	L
Value Priced Express Toll Lanes	1) check control systems frequently and keep them operating may cost the most; 2) barriers separate general lanes and toll lanes should be fixed if any damage			X		
Express Toll Lanes Non-Value Priced	1) check control systems frequently and keep them operating may cost the most; 2) barriers separate general lanes and toll lanes should be fixed if any damage			X		
HOV Lanes	1) signal systems and lane controllers maintenance cost; 2) also, cost for facilites seperating roadway, concurrent flow lanes and contraflow lanes sometimes need to be considered			X		
Truck Restricted Lanes	traffic signs and barriers replacement or renew if needed				X	
Non-tolled Express Lanes	barriers and lane access control system should be monitored if any damage			X		
HOT Lanes	1) barriers separate HOT lanes and signs for vehicle traveling indication are durable, may not cost highly in maintenance; 2) cost for signal systems and lane controllers need more attention in maintenance			X		
Exclusive Transitways	information signs on routes and stops' facilities need daily maintenance fees; traffic signal system also needs to be considered			X		
Exclusive or Dedicated Truck Lanes	few facilites existed, but signs for vehicle indications may need maintenance fees				X	
Multifaceted Managed Lanes	1) facilities and control systems from multiple strategies need proper incorporation; 2) sensors and loop detectors maintenance fees	X				
Dynamic Speed Limits	1) greatly increases the amount of field equipment to be maintained at a higher level than before; 2) maintenance considerations for overhead signs have to be factored into the design stage	X				
Part-Time Shoulder Use	1) highway appurtenances are closer to traffic and more subject to damage; 2) additional personnel and equipment might be needed to close lanes and provide adequate work-area protection during maintenance; 3) most incidents may require some action by personnel that involves shoulders; 4) emergency vehicles' use of shoulders to access scenes of accidents and delays in arriving on the scene			X		
Queue Warning	if portable detection or messaging is used, care must be taken to ensure communications and operations during work zone activity					X
Adaptive Ramp Metering	1) similar to regular traffic signal systems; 2) pole-mounted signal heads may be prone to knockdown by vehicles, requiring additional repair; 3) construction can affect detection systems					X
Dynamic Merge Control	no significant maintenance challenges beyond other lane control issues unless in-pavement lighting is used to support merge applications			X		
Dynamic Truck Restrictions	1) sensors and detection systems are mainly monitored and in maintenance; 2) facilities and signs for informing drivers may sometimes need to be renewed;				X	
Dynamic Rerouting and Traveler Information	1) alternative route used in this strategy should be taken care of thourgh ITS or other methods; 2) adequate sensor and sign infrastructure that are installed to obtain information			X		
Automated Enforcement	1) red lights and cameras operate frequently and need more inspection; 2) maintenance of signs on the roadsides, if needed			X		
Dynamic Lane Reversal	1) maintenance of pylons and lane separators is always a challenge when they are used to separate reversible lanes; 2) maintenance of core elements; maintenance of any ITS equipment and electronic signage and/or software can be significant			X		
Dynamic Lane Use Control	1) the health of the signs needs to be consistently monitored because of their importance; 2) replacement signs need to be available and need to be swapped as efficiently as possible			X		

Figure 33. Active management operational strategies vs. cost considerations / maintenance.

Active Management Operational Strategies	Application Geography				
	Freeway	Arterial	Interchange	Ramp	Intersection
Value Priced Express Toll Lanes	X				
Express Toll Lanes Non-Value Priced	X				
HOV Lanes	X	X			
Truck Restricted Lanes	X	X			
Non-tolled Express Lanes	X				
HOT Lanes	X				
Exclusive Transitways	X				
Exclusive or Dedicated Truck Lanes	X				
Multifaceted Managed Lanes	X				
Dynamic Speed Limits	X	X			
Part-Time Shoulder Use	X	X			
Queue Warning	X	X	X	X	
Adaptive Ramp Metering	X		X	X	
Dynamic Merge Control	X		X	X	
Dynamic Truck Restrictions	X	X	X		
Dynamic Rerouting and Traveler Information	X	X			
Automated Enforcement	X				X
Dynamic Lane Reversal	X	X			
Dynamic Lane Use Control	X	X			

Figure 34. Active management operational strategies vs. application geography.

Active Management Operational Strategies	Active Management Operational Strategies									
	Value Priced Express Toll Lanes	Express Toll Lanes Non-Value Priced	HOV Lanes	Truck Restricted Lanes	Non-tolled Express Lanes	HOT Lanes	Exclusive Transitways	Exclusive or Dedicated Truck Lanes	Multifaceted Managed Lanes	Dynamic Speed Limits
Value Priced Express Toll Lanes			X			X			X	X
Express Toll Lanes Non-Value Priced									X	X
HOV Lanes									X	X
Truck Restricted Lanes									X	X
Non-tolled Express Lanes									X	X
HOT Lanes									X	X
Exclusive Transitways									X	X
Exclusive or Dedicated Truck Lanes									X	X
Multifaceted Managed Lanes	X	X	X	X	X	X	X	X		X
Dynamic Speed Limits	X	X	X	X	X	X	X	X	X	
Part-Time Shoulder Use										X
Queue Warning	X	X	X	X	X	X	X	X	X	X
Adaptive Ramp Metering										X
Dynamic Merge Control					X				X	X
Dynamic Truck Restrictions				X					X	X
Dynamic Rerouting and Traveler Information	X	X	X	X	X	X			X	X
Automated Enforcement									X	
Dynamic Lane Reversal	X	X			X				X	X
Dynamic Lane Use Control	X	X			X				X	X

Figure 35. Compatible active management operational strategies.

Active Management Operational Strategies	Active Management Operational Strategies								
	Part-Time Shoulder Use	Queue Warning	Adaptive Ramp Metering	Dynamic Merge Control	Dynamic Truck Restrictions	Dynamic Rerouting and Traveler Information	Automated Enforcement	Dynamic Lane Reversal	Dynamic Lane Use Control
Value Priced Express Toll Lanes	X	X				X			X
Express Toll Lanes Non-Value Priced		X							X
HOV Lanes		X				X			
Truck Restricted Lanes		X			X	X			
Non-tolled Express Lanes		X		X		X			X
HOT Lanes		X				X			
Exclusive Transitways		X							
Exclusive or Dedicated Truck Lanes		X							
Multifaceted Managed Lanes		X		X	X	X	X	X	X
Dynamic Speed Limits	X	X	X	X	X	X			X
Part-Time Shoulder Use		X	X	X		X			X
Queue Warning	X		X	X	X	X			X
Adaptive Ramp Metering	X	X		X					X
Dynamic Merge Control	X	X	X			X	X		X
Dynamic Truck Restrictions		X	X	X			X		X
Dynamic Rerouting and Traveler Information	X	X		X				X	X
Automated Enforcement				X	X				
Dynamic Lane Reversal	X	X	X	X					X
Dynamic Lane Use Control	X	X	X	X	X	X			

Figure 36. Compatible active management operational strategies (continued).

Active Management Operational Strategies	Active Management Operational Strategies				
	Driver Alerts	Variable Message Signs	Incident Detection	Pre-travel Information	Speed Feedback Signs
Value Priced Express Toll Lanes	X	X	X	X	X
Express Toll Lanes Non-Value Priced	X	X	X	X	X
HOV Lanes	X	X	X	X	X
Truck Restricted Lanes	X	X	X	X	X
Non-tolled Express Lanes	X	X	X	X	X
HOT Lanes	X	X	X	X	X
Exclusive Transitways	X	X	X	X	X
Exclusive or Dedicated Truck Lanes	X	X	X	X	X
Multifaceted Managed Lanes	X	X	X	X	X
Dynamic Speed Limits		X			X
Part-Time Shoulder Use		X		X	X
Queue Warning	X	X	X	X	
Adaptive Ramp Metering		X			
Dynamic Merge Control		X		X	X
Dynamic Truck Restrictions		X			X
Dynamic Rerouting and Traveler Information	X	X	X	X	X
Automated Enforcement	X	X	X		X
Dynamic Lane Reversal		X		X	
Dynamic Lane Use Control	X	X	X	X	X

Figure 37. Compatible active management operational strategies (continued).

Active Management Operational Strategies	Potential Benefits													
	Delayed onset of main lane breakdown	Increased throughput	Improved level of service	Increased capacity	Reduced main lane travel delay	Increased on-time arrival	Reduced speed variability	Reduced speed differential	Improved travel time reliability	Increased travel speeds	Increased lane-level volumes	Increased vehicle occupancy	increased transit occupancy	increased goods movement
Value Priced Express Toll Lanes	X	X	X		X	X			X			X	X	
Express Toll Lanes Non-Value Priced	X	X	X		X	X			X			X	X	
HOV Lanes	X	X	X		X	X			X			X	X	
Truck Restricted Lanes	X	X	X		X	X			X					
Non-tolled Express Lanes	X				X	X			X					
HOT Lanes	X	X	X		X	X			X			X	X	
Exclusive Transitways	X	X	X		X	X			X			X	X	
Exclusive or Dedicated Truck Lanes	X	X	X		X	X	X	X	X					X
Multifaceted Managed Lanes	X	X	X		X	X			X			X	X	
Dynamic Speed Limits	X		X		X	X	X	X	X					
Part-Time Shoulder Use	X	X	X	X		X			X	X	X			
Queue Warning	X		X		X	X	X	X	X	X				
Adaptive Ramp Metering	X	X	X		X	X	X	X	X	X				
Dynamic Merge Control	X	X	X	X	X	X	X	X	X	X	X			
Dynamic Truck Restrictions	X	X	X		X	X	X	X	X	X				X
Dynamic Rerouting and Traveler Information			X		X	X			X					
Automated Enforcement						X	X	X						
Dynamic Lane Reversal	X	X	X		X	X			X	X	X			
Dynamic Lane Use Control	X		X	X	X	X			X	X	X			

Figure 38. Active management operational strategies vs. potential benefits.

Active Management Operational Strategies	Potential Benefits													
	Reduced queue lengths	Reduced ramp delay	Reduced number of stops	Reduced vehicle hours traveled	Reduced arterial travel time	Reduced travel time	Reduced arterial travel delay	Reduced travel delay	Increased arterial speeds	Reduced intersection delay	Reduced crash rates	Reduced secondary accidents	Improved responder safety	Reduced crash severity	Reduced spatial extent of congestion
Value Priced Express Toll Lanes				X		X		X			X				
Express Toll Lanes Non-Value Priced				X		X		X			X				
HOV Lanes				X		X		X			X				
Truck Restricted Lanes				X		X		X			X				
Non-tolled Express Lanes				X		X		X							
HOT Lanes				X		X		X			X				
Exclusive Transitways				X		X		X			X				
Exclusive or Dedicated Truck Lanes				X		X		X			X				
Multifaceted Managed Lanes				X		X		X			X				
Dynamic Speed Limits				X				X			X			X	X
Part-Time Shoulder Use				X		*		X			X	X	X	X	
Queue Warning	X		X	X				X			X	X			
Adaptive Ramp Metering	X	X	X	X				X			X	X		X	
Dynamic Merge Control	X	X		X		X		X			X	X			
Dynamic Truck Restrictions				X		X		X			X	X		X	
Dynamic Rerouting and Traveler Information	X		X	X		X		X			X	X			
Automated Enforcement														X	
Dynamic Lane Reversal	X		X	X	X	X	X	X	X	X	X				
Dynamic Lane Use Control	X		X	X		X		X			X	X	X	X	

Figure 39. Active management operational strategies vs. potential benefits (continued).

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The National Institute for Congestion Reduction (NICR) will emerge as a national leader in providing multimodal congestion reduction strategies through real-world deployments that leverage advances in technology, big data science and innovative transportation options to optimize the efficiency and reliability of the transportation system for all users. Our efficient and effective delivery of an integrated research, education, workforce development and technology transfer program will be a model for the nation.

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