Environmental Impacts of Congestion Management Strategies: A White Paper

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ABSTRACT

This white paper summarizes the findings from a critical review of literature supplemented by interviews with subject experts and public agency staff on environmental impacts of congestion management strategies. Emphasis is placed on the quantitative impacts of operational strategies on vehicle miles traveled (VMT), and greenhouse gas (GHG) pollutant emissions. Examples of strategies include traffic signal timing, ramp metering, transit signal priority, variable speed limits, temporal shoulder use, dynamic lane utilization, integrated corridor management, incident management and traveler information and guidance. The review also addresses the environmental impacts of emerging transportation technologies such as connected and automated vehicles (CAVs) and the challenges to accurately assess their impacts, given the limitations of existing modeling tools to accurately model driver-vehicle characteristics and interactions, much less predict their broader impacts. Also, the impacts of CAVs are difficult to estimate because they depend on the penetration rate in various operating environments, which will be a function of vehicle ownership and operation costs, consumer preferences, intended vehicle uses, operating environment, and public policy. Recommendations are provided for developing analysis procedures to predict the interactions of congestion measures that reduce GHG and the VMT changes in the short and long term.

ACKNOWLEDGMENTS

EXECUTIVE SUMMARY

Objectives and Research Approach

This white paper summarizes the findings from a critical review of literature supplemented by interviews with subject experts and public agency staff on environmental impacts of congestion management strategies.

A comprehensive inventory of congestion mitigation measures was developed in cooperation with the research team working on the social equity impacts of congestion management strategies [1] through reviewing the literature and receiving feedback from CARB staff members. We divided each of these individual strategies into six broad categories, including: 1) pricing, 2) parking and curb policies, 3) operational strategies, 4) infrastructure changes, 5) transportation services and strategies, and 6) conventional taxation.

The white paper focused on the environmental impacts of operational strategies classified into control strategies (traffic signal timing, ramp metering, transit signal priority, variable speed limits, queue warning systems), geometric strategies (dynamic lane assignment, dynamic lane restrictions, temporal shoulder use, managed lanes, complete streets) and demand management strategies (traveler information, route guidance, dynamic parking). Emphasis is placed on the interaction of traffic operating conditions and the time spent in driving modes and the quantitative impacts of operational strategies obtained from estimates of performance measures, or measures of effectiveness (MOEs, i.e., vehicle miles traveled (VMT), and greenhouse gas (GHG) pollutant emissions). The review also addressed the data requirements and tools for estimating the MOEs, the interaction of traffic flow improvements and emissions, plus the emerging transportation technologies such as connected and automated vehicles (CAVs) and the challenges to accurately assess their environmental impacts.

Findings

The congestion management strategies described in this white paper typically can reduce GHG emissions in the range of 5% to 15%. Greater benefits may be achieved when a combination of measures are implemented as currently pursued by the Integrated Corridor management (ICM) program. The amount of benefits depend on the type of improvements, traffic patterns and driver and vehicle characteristics (e.g., lower benefits are expected with the prevalence of electric and hybrid vehicles on the network). Also, a high % of emissions reduction does not necessarily indicate a high amount of pollutants saved.

Fuel consumption and emissions estimates in congestion management projects are typically derived from mobility related MOEs (travel time, speed, stops), and

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[1] Shaheen, S., A. Stocker, and R. Meza, "White Paper: Social Equity Impacts of Congestion Management Strategies," prepared for the California Air Resources Board, Transportation Sustainability Research Center, November 2019.

VMT based on analysis procedures that may not accurately calculate these impacts. There is a lack of multimodal optimization tools to minimize mobility related MOEs, emissions and VMT.

Operational strategies consisting of temporal capacity additions (re-allocation of travel lanes, temporal shoulder use) are cost effective to congestion and safety problems, compared to capacity expansion projects (new highways or additional lanes). More important the temporal lane addition does not generate induced demand, which typically occurs after permanent lane additions. However, their environmental impacts following implementation have not been documented. This is also the case for managed lanes involving lane use restrictions.

A significant amount of research focuses on the impacts of CAVs. Simulation results indicate that CAVs operating under existing traffic management strategies may further reduce fuel and emissions by 2 to 22%. There is limited empirical evidence regarding the behavior and impacts of CAVs on traffic performance. Further uncertainties in the predictions are due to behavioral changes that may lead to VMT increases.

Recommendations for Future Research

A number of research needs identified the technology required for the implementation of advanced strategies, analysis tools for assessing their effectiveness, and understanding of the connection between environment, mobility, and safety performance of any congestion reduction program.

Technology Requirements: There is a need for comprehensive evaluation studies to determine the type and function of the infrastructure required for the deployment of advanced strategies and the associated lifetime costs. Examples include emerging non-intrusive surveillance technologies information on traffic conditions, upgrade of traffic signal systems and their interconnections, and dedicated short range communications (DSRC) for CAV applications.

Estimation of Fuel Consumption and Emissions: Accurate estimation of vehicle emissions and fuel consumption requires the time spent in each driving mode. Currently, new technologies and algorithms provide field collection of vehicle trajectory data and clustering at various traffic states. There is a need to develop methodologies that utilize the real-world trajectory data for emissions estimation.

Traffic Analysis Tools: Existing traffic analysis tools are not well suited for evaluating CAVs and other emerging technology applications. Agencies need specific guidance on the application of existing tools and their limitations for modeling

CAV equipment, modeling driver behavior, modeling CAV applications and the driver responses.

Framework for Environmental Assessment of Congestion management Strategies: There is a need to develop a framework for evaluating the performance of congestion management projects that accurately models the interactions of traffic flow improvements and emissions. The proposed framework should include a land use model that is sensitive to changes in transportation network conditions, an activity-based travel demand model and a dynamic traffic assignment. The framework should be able to present the impacts in the form of benefit-cost analysis to facilitate communication of the benefits of strategies to decision-makers.

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CHAPTER 1.
INTRODUCTION

New approaches for improving mobility, accessibility and safety are beginning to challenge conventional approaches to transportation system design and operation and change planning processes. Local agencies in California and elsewhere are implementing innovative strategies to manage traffic congestion, including adaptive traffic control, smart parking operations, transit signal priority, new mobility services, new infrastructure designs to support multimodal operations, and congestion pricing. Research and development on new transportation technologies point to large-scale change in the mid- to long-term.

This white paper describes congestion management strategies implemented in or relevant to California and their environmental impacts based on a critical literature review supplemented by interviews with key staff members at agencies implementing new strategies and pilot projects to address traffic congestion. The paper synthesizes the literature and reports on the near- and long-term impacts of congestion management strategies. Throughout the paper preparation close cooperation was maintained with the research team preparing the companion white paper on "Social Equity Impacts of Congestion Management Strategies".

Critical Issues

Congestion management strategies may have complex impacts on vehicle miles traveled (VMT), and greenhouse gas (GHG) emissions. Further, because transportation technologies and services are in a transformational period, future opportunities and impacts may be different from those experienced in the past.

The assessment of environmental impacts of congestion management strategies needs to address several critical issues as described below.

Performance Measures

Transportation performance measures (Measures of Effectiveness – MOEs) are used to evaluate and monitor the performance of projects for improving mobility. MOEs vary with the context and operating conditions. MOEs typically used on freeways include average travel time on the freeway mainline (minutes, or minutes /mile), travel time index (ratio of the average travel time to the free flow travel time), total delay, travel time reliability VMT, and bottleneck discharge rate. On-ramps are assessed based on average delay, queue length, and time that the queue detector is active in the case of ramp metering. In urban networks controlled by traffic signals, average delay and the number of stops are the key measures. Additional MOEs have been proposed by Caltrans in the "smart mobility 2010: a call to action" initiative (California Department of Transportation, 2010). These include multimodal reliability measures and social equity metrics.

The choice of MOEs depends on how accurately and robustly the analyst wishes to track the effectiveness of the implemented strategies, and the data and analysis tools required for the estimation of the MOEs. Analysts may add other performance measures to account for other benefits and costs of congestion management strategies. For instance, communities may raise concerns about traffic diverted to local streets by congestion pricing or other user charges on particular facilities, or due to freeway ramp metering.

MOEs used to assess the environmental impacts of projects such as fuel consumption and GHG emissions are difficult to measure in the field and typically are calculated using analytical tools from other MOEs such as average speed, travel time, delay and stops. This approach depends on the assumptions used in the relationships of the surrogate measures and emissions and may not accurately assess the environmental impacts of certain strategies, e.g., reduction in the number of stops on arterials. Further, many environmental impacts assessment require data on receptors, populations affected, etc. Some of these data are available from the Census, regional planning agency data bases, or local studies, but some require public involvement because local knowledge and opinion are critical to the assessment.

Data Requirements

Field data are critical for the development and assessment of congestion management strategies. At the same time, field data collection is an expensive and time-consuming process. Continuous technological developments provide traffic monitoring systems with better sensor technology, more reliable communication channels, and more advanced information processing capability. Examples include the Freeway Performance Measurement System (PeMS) (Choe, 2002) that provides a database of operating conditions on California freeways based on loop detector data. The commercial INRIX database (Sharma, 2017) provides travel times on freeways and arterial streets in most metropolitan areas in the US based on data from fixed detectors and mobile sources. The National Performance Management Research Data Set (NPMRDS) provided by the FHWA is a database of travel times on the US major highways (Kaushik, 2015). Other data sources include blue tooth data, GPS traces and mobile phone matched position records for providing origin-destination and travel time information (Streetlight, 2018).

In addition to the availability of field data from various sources, there is a need for analysis tools to take advantage of the new data sources to estimate the performance measures necessary for tracking the performance of congestion management strategies. New data processing and analysis techniques are being developed to determine the system state (traffic flow, density, and speed on the highway facility) as well as other microscopic traffic parameters. This real-time

traffic information can be used for better traffic system management to reduce congestion and emissions.

Strategies Trade-offs and Synergies

The implementation of congestion reduction and parking strategies involves trade-offs and also opportunities for synergies among strategies.

Figure 1.1 illustrates the complex interactions of traffic flow improvements and mobile emissions (Dowling and al, 2005). Operational improvements that reduce congestion, improve vehicle operating speeds, reduce stop-and-go conditions, which reduces acceleration and deceleration events that result in lower emission rates. Also, cruising at higher operating speeds may also decrease emissions. However, higher speeds result in lower travel times that may encourage drivers in the short term to make additional trips on the facility or change their mode, route and time of travel. Longer term effects may include relocation of traveler and businesses to take advantage of the improved traveling conditions. These effects may result in higher VMT and reduction of the initial emission and travel time savings.

As noted, congestion management projects are increasingly evaluated not only according to traffic MOEs, but also taking into consideration environmental impacts such as GHG and criteria pollutant emissions. However, some congestion management interventions may have other environmental consequences that are important. For example, freight management strategies can reduce truck idling in dense urban areas and spillover of truck traffic onto local streets and arterials, reducing exposures to health and safety hazards. Parking pricing strategies can help induce mode shifts away from the automobile, but also may induce some parkers to seek spaces in residential neighborhoods. Also, traffic improvements for one mode may adversely affect the accessibility and traffic operations for other modes. Intersection widening to allow exclusive turn lanes that reduce vehicle delays will increase pedestrian crossing times.

Role of Emerging Technologies

As computer and communication technologies continue to improve, new transportation applications are being developed and tested for improving mobility and safety.

Connected Vehicles refer to the ability of vehicles to communicate wirelessly with other vehicles (V2V), with the roadway infrastructure (V2I), such as traffic signals, and with other non-motorized roadway users such as pedestrians and bicyclists (V2X). Vehicle automation (AV) actively pursued by most vehicle manufacturers and high technology companies aims to produce self-driven vehicles that will be able to operate in all operating environments.

While the timing for full vehicle automation is debated and initial applications may be limited to particular facilities or vehicle types, connected automated vehicles (CAVs) will increasingly operate to all highway facilities. The impacts of CAVs are difficult to estimate because they depend on the penetration rate in various operating environments, which will be a function of vehicle ownership and operation costs, consumer preferences, intended vehicle uses, operating environment, and public policy. Existing modeling tools have limited ability to accurately model driver-vehicle characteristics and interactions for CAVs, much less predict their broader impacts.

Traffic-Flow Improvements

1. Operational Improvements
   - Higher Speeds
   - Fewer Acceleration Events

2. Short-Term Demand Changes
   - More Trips & Farther Trips
   - Change Mode, Route, Schedule

3. Long-Term Changes
   - Relocate Home/Business

Lower/Higher Emission Rates

More VMT More Trips

Mobile Source Emissions
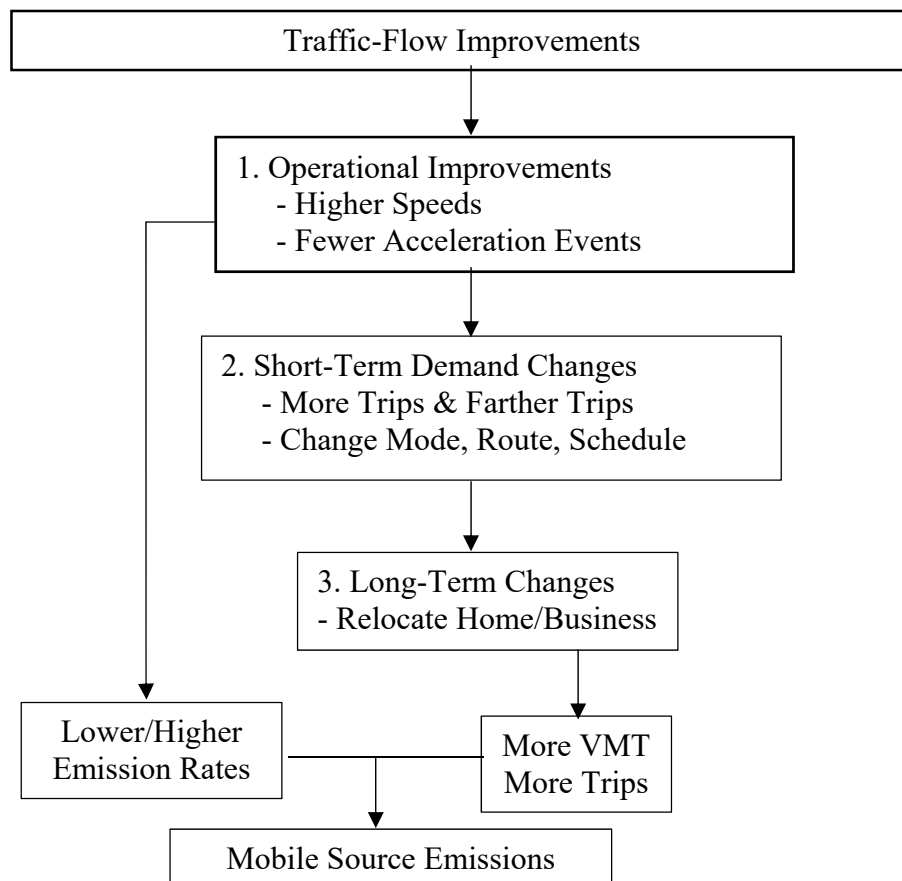
Figure 1.1 Operational Improvements vs. Emissions (Dowling et al, 2005)

Organization of the Report

The next chapter describes congestion management strategies and their environmental impacts based on the literature review, and presents the key findings from the interviews with transportation experts. Chapter 3 summarizes the research findings and identifies critical research needs.

CHAPTER 2

LITERATURE REVIEW

It is commonly known that the transportation sector is responsible for nearly one-third of GHG emissions (US EPA, 2015). In California, transportation is responsible for over 40% of GHG emissions (CARB, 2017). The amount of GHG emissions depend on the vehicle activity during a trip, i.e., the time spent in each driving mode (acceleration, deceleration, idle and cruise). As illustrated in Figure 2.1 this amount depends on the vehicle type, driver behavior, roadway facility type and characteristics and traffic conditions (Barth, 2009). In order to reduce these GHG contributions, efforts have been focused on: 1) improving overall vehicle fuel economy (e.g., using more efficient innovative drivetrains, reducing weight while maintaining safety); 2) using less carbon-intensive fuels (e.g., ethanol, electricity), 3) managing travel demand (e.g., roadway tolling, shifting travel to non-motorized modes) and 4) improving the efficiency of transportation system operations. Intelligent Transportation Systems (ITS), the application of information technology to transportation systems, bring new opportunities to develop and implement new strategies to reduce traffic congestion, improve safety, and reduce GHG emissions and energy consumption.
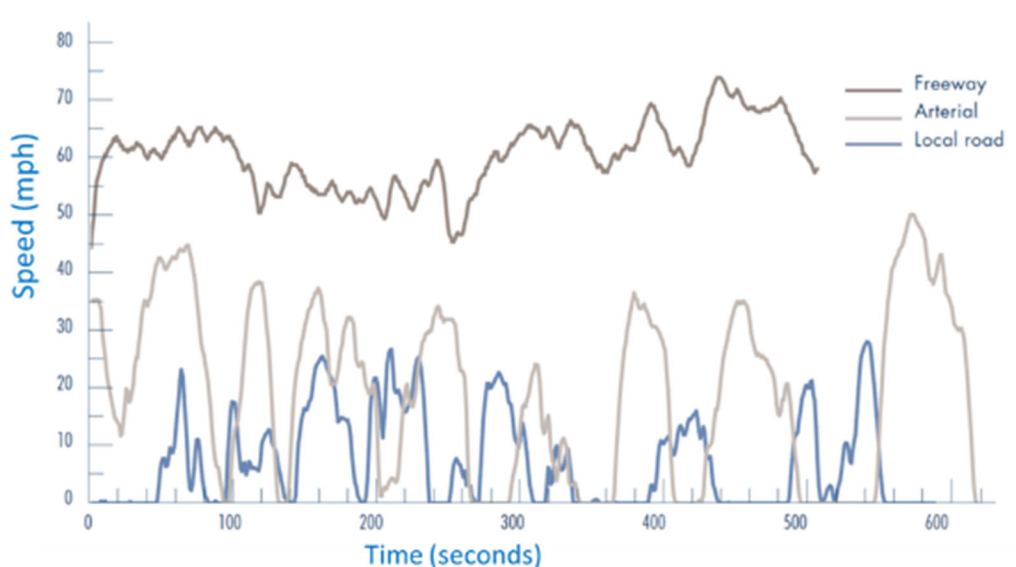

Figure 2.1 Typical Vehicle Speed Profiles for Different Roadway Types and Conditions (Barth, 1997)

Traffic operating conditions have a significant impact on the vehicle's driving mode. Figure 2.2 shows time spent per driving mode based on measured field data from I-880 freeway in the Bay Area (Skabardonis, 1997). In undersaturated conditions (volume/capacity ratio v/c less than 0.90) most of the time vehicles travel at cruise speed and spend little time in the acceleration/deceleration modes. In oversaturated conditions however (demand volume/capacity v/c greater than 1), most of the time is spent at low speed and acceleration and deceleration events, which generate a high amount of air pollutant emissions. Strategies to mitigate freeway congestion, including; ramp metering, demand reduction, and speed harmonization collectively will provide improved air pollution reduction benefits. However, certain strategies may raise equity concerns related to the non-equitable distribution of impacts or non-equitable distribution of access and mobility, as discussed in the companion paper.

a) undersaturated   b) oversaturated
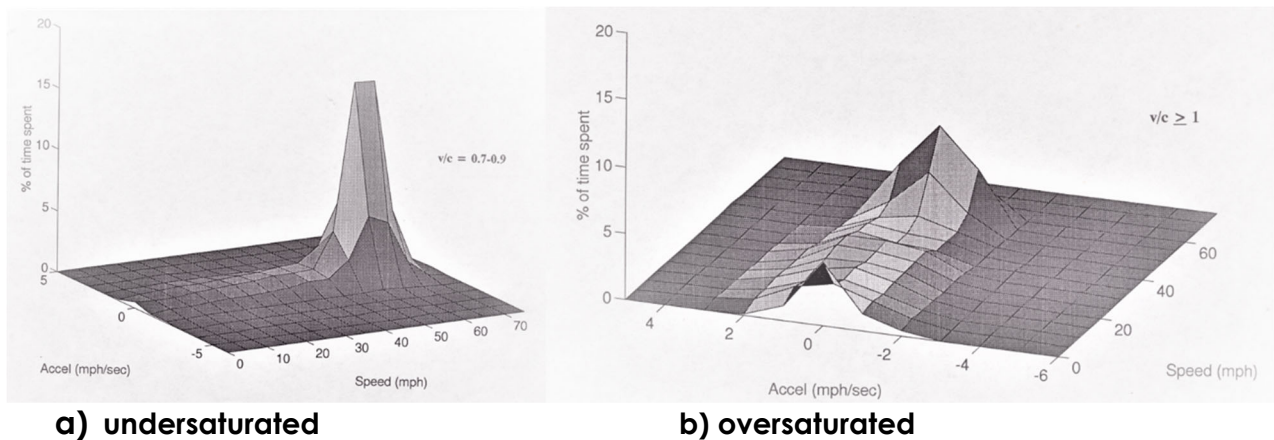
Figure 2.2 Impact of Freeway Operating Conditions on Time Spent per Driving Mode (Skabardonis, 1997)

2.1 Existing Congestion Management Strategies

A comprehensive inventory of congestion mitigation measures was developed in cooperation with the research team working on the social equity impacts of congestion management strategies through reviewing the literature and receiving feedback from CARB staff members (Table 2.1). We divided each of these individual strategies into six broad categories, including: 1) pricing, 2) parking and curb policies, 3) operational strategies, 4) infrastructure changes, 5) transportation services and strategies, and 6) conventional taxation. Table 2.1 also shows the impacts of the strategies on air pollutant emissions (GHC), amount of vehicular travel (metric used vehicle-miles of travel, VMT), and mobility (metric used travel time, TT) expressed as the % changes reported in the literature "before" and "after" the implementation of the selected strategy.

Figure 2.3 shows a functional classification of the congestion management strategies shown in Table 2.1. Note that most of the travel demand management (TDM) strategies that focus on the reduction and substitution of travel to other modes do not result in travel time changes, and thus there is no travel time change reported in table 2.1. In contrast, the control management strategies produce mobility benefits and no changes in traffic demand.

The review in this paper focuses on existing operational strategies with emphasis on implemented projects. The values shown in Table 2.1 represent the best information obtained from the critical review of the literature and in a number of strategies the information is not available (NA). Note that there are no values reported for strategy 4.7 (infrastructure road improvements) because this strategy leads to increase in the VMT based on several studies (Boarnet, 2017). Also, impacts are not reported for strategy 6.1 (fuel taxes) because it requires extensive analyses of several factors over a long period of time that is outside the scope of the project.

Table 2.1 Environmental Impacts of Congestion Management Strategies—Impacts Summary

#	Congestion Management Strategy		GHG	VMT	TT
1	**Pricing**				
1.1	Cordon/Area pricing	Fees applied to motorists when entering and/or circulating in a specified area, typically a Central Business District (CBD). *Non US experience	8*	8*	
1.2	Distance-based pricing	Motorist pays fees on a per distance basis. Similar to Road Usage Charge (RUC), Mileage Based User Fee (MBUF), and vehicle miles traveled (VMT) fees. Could include restricted access to specified areas or lanes where fee applies.	NA	NA	
1.3	Dynamic congestion pricing	Pricing on a tolled facility (or area) that fluctuates based on congestion levels. Price increases with increased congestion.	NA	NA	NA
1.4	Means-based pricing	Pricing based on income level. Could be applied to public transit fares, road pricing, or other transportation-related fees.	NA	NA	NA
1.5	Flat-rate pricing	Motorist pays set price to use tolled facility. Facilities could include highways, bridges, tunnels, or other infrastructure.	NA	NA	NA
1.6	Full-facility tolls	Motorist pays to use tolled facility in which prices could fluctuate. The fee applies to every motorist entering the facility.	NA	NA	NA
1.7	Managed lanes	Fees or regulations applied on specified lanes. Could include high occupancy vehicle (HOV) lanes (lanes dedicated to motorists with a minimum passenger requirement), high occupancy toll (HOT) lanes (HOV or fee paid if HOV requirement not met), or express lanes (fee paid to use lane, regardless of the number of passengers). *case studies of HOT/HOV conversions	10 (-15)*	2 (-20)*	10 (15*
2	**Parking and Curb Policies**				

2.1	Dynamic parking pricing	Parking fees that fluctuate based on demand. Fees increase as parking availability decreases.	6	6	
2.2	Off-street parking pricing/policy	Could include tax on parking facilities or reduced parking requirements for development.			
2.3	Parking navigation tools	Technology that assists drivers in locating available parking. May use satellite imaging or sensors to identify either on-street or off-street parking.			
2.4	Curbside management	Organizing and allotting curb space for bikesharing or scooter sharing, deliveries, passenger pick-up and drop-off, American Disability Act (ADA) access, emergency vehicles, automated vehicles (AVs) and shared automated vehicles (SAVs), and other potential uses.	NA	NA	
2.5	Parking cash out	Employers offer a cash payout to employees instead of free parking at place of employment.	NA	NA	
3	**Operational strategies**				
3.1	Traffic signal priority (TSP)	Modified traffic signal timing that gives priority to public transit (e.g., buses); bikes; and/or pedestrians for the purpose of reducing travel time among users of these modes and increasing safety *impacts to transit vehicles*	10*		10*
3.2	Traffic responsive / adaptive arterial signal control	Optimization of signal timing plans at traffic signals and signal coordination along arterials to minimize delays and stops.	15		20
3.3	Ramp metering	Traffic signaling to regulate the flow of traffic from highway on-ramps. Recent strategies include coordinated adaptive ramp metering and cooperation with dynamic speed limits and signal control of adjacent traffic signals.	17		12
3.4	Variable	Dynamic speed advisories to reduce	10		10

	Speed Limits	speed variations during congested conditions.			
3.5	Dynamic Lane Control	Dynamic designation of lane usage to accommodate surges in traffic movements (merging/diverging/weaving) *Under incident and work conditions*	11*		11*
3.6	Temporal Shoulder Use	Temporal use of shoulders as mainline travel lanes on freeways to alleviate traffic congestion subject to safety constraints.	7		7
3.7	Managed lanes	Restrictions on the use of travel lanes by certain vehicle classes (e.g., trucks) or movements (left turns at signalized intersections).	*Strategy 1.7*		
3.8	Multimodal Traveler Information	Real-time information on travel times and roadway conditions based on data from infrastructure detectors and probe vehicles and smart phones.	5		5
3.9	Queue Warning Systems	Driver alert of congestion formed traffic queues that are potential safety hazards (used in combination with variable speed limit and lane control systems).	NA		NA
3.10	Incident management	Procedures, equipment for quick detection, response and removal of traffic incidents and crashes.	3		7
3.11	Geofencing	Technology that uses a virtual boundary for a physical area. Could physically stop vehicles or other modes (e.g., automated vehicles or e-scooters) or simply alert motorists/travelers when crossing a boundary.	NA	NA	
3.12	Public transit improvements	Could include increased capacity, dedicated lanes (e.g., bus rapid transit); frequency; attractiveness (e.g., WiFi, A/C) and/or improved real-time transit information; public transit planning technology; or timed transfers.			
4	**Infrastructure Changes**				
4.1	Park and ride	Parking lots or structures located			

	facilities	immediately next to public transit connections and typically outside of congested central business districts (CBDs).			
4.2	Transit oriented development (TOD)	Mixed land-use development centered around major transit connections and designed to encourage active transportation within the area.	NA	NA	
4.3	Car-free zones	Areas that prohibit all vehicles or most private vehicles. Also known as pedestrian zones.	NA	NA	
4.4	Road diet	A reduction of lanes and/or a narrowing of lanes usually to provide bike lanes, public transit only lanes, and/or parklets, as well as to reduce vehicle speeds.			
4.5	Pedestrian and bicycle infrastructure improvements	Design that enhances safety and encourages active transportation. Includes well-maintained sidewalks, safe crossings, universal design, improved path connectivity, protected bike lanes, increased bike parking, visual attractiveness, and other elements.			
4.6	Complete Streets	Control improvements in addition to design listed in 4.5 to facilitate efficient ad safe travel for all road users (auto, transit, pedestrians, and bicycles).			
4.7	Increased road capacity	Creating additional lanes or building new roads, freeways, bridges, or tunnels.			
5	**Transportation Services and Strategies**				
5.1	Shared mobility (automotive)	Shared use of a transportation mode involving an automobile (e.g., carsharing, carpooling, TNCs, microtransit, etc.) to decrease the need for private vehicle ownership and reduce travel demand.	10 (-6)*	10 (-6)*	
5.2	Shared mobility (active)	Shared use of an active transportation mode (e.g., bikesharing, scooter sharing, etc.) to decrease the need for private vehicle ownership and reduce travel demand.	NA	NA	

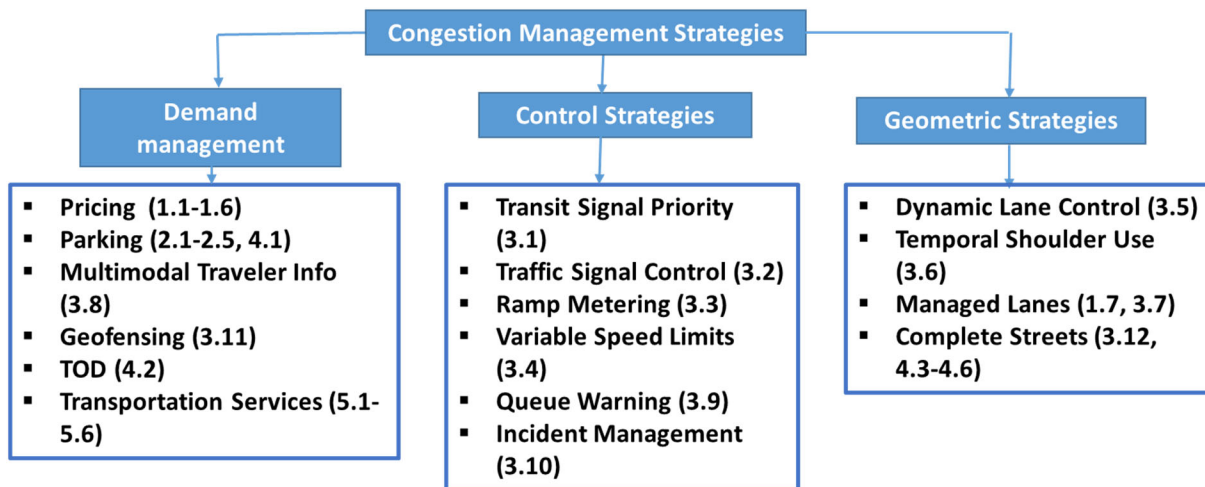| 5.3	Courier network services (CNS)	Typically, app or web-based platforms allowing customers to purchase goods and have them delivered to their home. Delivery could be within the hour or within a few days of ordering, depending on service.	NA	NA	
5.4	Pay as You Drive (PAYD) Insurance	A type of auto insurance in which cost is based on distance traveled and is often combined with conventional auto insurance factors (e.g., driving history). It may also take into account how, when, and where driving occurs, using tracking technology which collects data from the vehicle directly.	2	8	
5.5	Fleet pricing	Fees applied to entire fleets of vehicles when in operation, such as taxis, TNC, carsharing vehicles, micromobility vehicles (e.g., bikesharing, scooter sharing), SAVs, and delivery/commercial vehicles.	NA	NA	
5.6	Telecommuting/ flexible work hours	Employees work from home (or at work hubs close to home) and/or have staggered/flexible work hours to avoid peak travel periods.	1	1	
6	**Conventional Taxation**				
6.1	Fuel taxes	Tax applied per unit of fuel purchased.			

Figure 2.3 Classification of Congestion Management Strategies

2.1.1 Demand Management

This section addresses the demand management strategies listed in Table 2.1 as they are grouped in Figure 2.3 that mostly related to the operation of transportation facilities. A comprehensive list of travel demand management (TDM) strategies can be found on the Online TDM Encyclopedia (Virginia Transport Policy Institute, 2019). Most of the previous studies on environmental impacts of TDM strategies consider the combination of strategies in a region. A study by EPA on the TDM impacts on emissions (EPA, 2011) used data from representative metropolitan regions in the country to evaluate the reduction from land use policies, transit-related strategies and parking and road pricing. The results indicate that emissions and VMT are reduced by 1% to 4% by the year 2030, and by 3% to 8% by the year 2050, depending on the combination of strategies applied. Similar trends (2% to 6% during a 10-year time horizon) were reported from a review of several modeling impacts of these strategies in California and overseas (Rodier, 2009).

Pricing (Strategy 1.1-1.6): Fees applied to motorists when entering and/or circulating in a specified area, typically a Central Business District (CBD). Implementations of this strategy on a broad scale has resulted in 10-14% drop in emissions in the central areas of the cities of London, Singapore and Stockholm (FHWA, 2014). Simulation evaluation of congestion pricing using the network of Delaware as a case study found a 10% reduction in emissions (Daniel, 2000). Projected benefits of 10% in emissions reduction are estimated from toll pricing in the cities of Boston and Seattle (IBBTA, 2018).

Active Parking Management (Strategies 2.1, 2.2 and 2.3): Technologies that provide drivers with real-time guidance to parking facilities with available capacity, adjust parking prices in response to prevailing demand/availability, and activate overflow parking facilities when existing ones approach capacity. Through sensors under parking spaces with online and smartphone applications, drivers can identify when and where parking is available at their destination. Active parking management reduces the traffic congestion associated with "cruising" for a parking space and the excess air pollution associated with idling and circling city blocks searching for available parking. The evaluation of the SFpark active parking management program in San Francisco shows a 6% reduction in greenhouse gas emissions (SFMTA, 2014).

Parking Cash-out (Strategy 2.5): Employers offer a cash payout to employees instead of free parking at place of employment. The evaluation of the program in eight locations indicates that both VMT and emissions were reduced by 12%. (Shoup, 1997). (Rodier, 2009). Another study reports that employee parking pricing may result in approximately a 1% reduction in VMT (Rodier, 2009).

Park and ride facilities (Strategy 4.1): Parking lots or structures located immediately next to public transit connections and typically outside of congested central business districts (CBDs).

Multimodal Traveler Information (Strategy 3.8): Traveler information systems provide information to network users on current roadway conditions, including delays, incidents, adverse weather, travel times, emergency alerts, and alternate routes. Travel information is generated by surveillance devices (sensors, cameras) reporting to a traffic management center or through private entities using data from in-vehicle location devices, or from smart phones communicating location and speed. This information is then disseminated via traditional broadcast media, internet, mobile devices, or roadside messaging.

Traveler information to drivers before and during trips allows them to make more effective travel decisions about changing routes, modes, departure times, or even destinations. Reported benefits vary widely from 2% to 25% reductions in fuel consumption, emissions and travel time depending on the traffic and network characteristics and the information accuracy and timeliness (USDOT, 2018). The availability of timely and reliable multimodal travel information is also a TDM strategy that reduces the demand for roadway travel by single occupancy vehicles (SOVs) (ITS JPO and ITE, 2017a). Travelers can use their cell phones to find transit routes and schedules from their current location or from a proposed departure point to a planned destination, and to check the arrival time of transit vehicles. However, guidance to divert to local streets from congested freeways may create congestion and delays to the local roadways that have not been designed to accommodate the routed traffic volume.

Conventional approaches to assign traffic to travel routes are based on minimization of either the individual's travel time (UE-user equilibrium) or total system travel time (SO- system optimum). Research has shown that an emission-optimized traffic assignment model using emission factors developed for CARB (California Air Resources Board, 2010) can reduce emissions by 8-30% compared to the time-dependent UE and SO conditions (Sugawara and Niemeier, 2002). The emission-optimized assignment is most effective when the network is under low to moderately congested conditions. The findings from another study also provide convincing evidence that a UE and SO traffic assignment does not necessarily minimize vehicle fuel consumption and emissions based on the second-by-second GPS commute field data on a real world network of freeways and arterials and the simulation results (Ahn and Rakka, 2008).

Geofensing (Strategy 3.11): Technology that uses a virtual boundary for a physical area. Could physically stop vehicles or other modes (e.g., automated vehicles or e-scooters) or simply alert motorists/travelers when crossing a boundary. Currently, there is a limited use of Geofencing in transportation systems, and there no findings on its effectiveness in emissions and VMT reduction. It is expected that Geofensing to be used more because it provides the tool to dynamically manage the traffic at congested corridors and designate car free zones at city neighborhoods. Currently the technology is part of the City of Riverside innovation corridor, a test bed for implementing and testing advanced technologies operated by the CE-ERT research center (City of Riverside, 2019).

Transit oriented development (TOD) (Strategy 4.2): Mixed land-use development centered near major transit connections and designed to encourage active transportation within the area. TOD developments along with ridesharing and improved transit service were found as cost-effective strategies for reduction of GHG emissions in a study conducted by the Los Angeles Metropolitan Transportation Authority (Gallivan, 2011).

Transportation Services-Shared Mobility automotive & active (Strategies 5.1, 5.2): Shared use of either a transportation mode involving an automobile (e.g., carsharing, carpooling, TNCs, microtransit,) or an active transportation mode (e.g., bikesharing, scooter sharing, etc.) to decrease the need for private vehicle ownership and reduce τηε τοταλ travel demand. Studies have shown that carsharing and bikesharing reduce VMT and greenhouse gas emissions (Shaheen et al., 2015). The results from analysis of carsharing in five cities indicate an average reduction of 11% in VMT and emissions per household (Martin, Shaheen, 2016).

While automotive shared mobility modes have the potential to decrease congestion (e.g., carpooling), others may increase congestion in certain contexts.

A study of transportation network company (TNC e.g., Lyft and Uber) impacts on congestion in San Francisco found that 6.5% in VMT (SFCTA, 2017) and 51 % of the increase in daily vehicle hours of delay between 2010 and 2016 was attributable to the introduction of TNCs (SFCTA, 2018).

Courier network services (CNS) (Strategy 5.3): Typically, app or web-based platforms allowing customers to purchase goods and have them delivered to their home. Delivery could be within the hour or within a few days of ordering, depending on service. Currently, there are no data available for the impact of courier services on congestion (VMT) and emissions (SFMTA, 2018).

Transportation Services-Pay as you Drive Insurance (PAYD) (Strategy 5.4): A type of auto insurance in which cost is based on distance traveled and is often combined with conventional auto insurance factors (e.g., driving history). A study conducted by the Brookings Institution suggest that PAYD would result in an 8% VMT reduction and 2% reduction of greenhouse gas (GHG) emissions in California (Bordoff, 2008). In another study was reported that PAYD may produce reductions ranging from 4% to 5% over all time horizons (Rodier, 2019).

Transportation Services-Fleet Pricing (Strategy 5.5): Fees applied to entire fleets of vehicles when in operation, such as taxis, TNC vehicles, carsharing vehicles, micromobility vehicles (e.g., bikesharing, scooter sharing), SAVs, and delivery/commercial vehicles. Currently, there are no data available on the impacts of this strategy to VMT and emissions.

Transportation Services-Telecommuting/flexible work hours (Strategy 5.6): Employees work from home (or at work hubs close to home) and/or have staggered/flexible work hours to avoid peak travel periods. The findings of a nationwide study suggest a reduction in annual VMT on the order of 0.8% or less (Choo, 2005).

2.1.2 Control Strategies

The application of control strategies in traffic operations and management began more than fifty years ago, since the introduction of digital computers. The continuous developments in computer technology and communications have created opportunities for active traffic and demand management (ATDM) strategies designed to manage traffic conditions in urban networks based on real-time data and predictive algorithms (FHWA, 2007, Fuhs, 2010).

Transit Signal Priority (TSP) (Strategy 3.1): TSP adjusts the settings at signalized intersections to give priority to busses. Passive strategies adjust the signal settings on arterials to provide progression to the buses taking into account the slower bus speed and the midblock dwell times. Active strategies detect the arrival of the

bus and may hold the green until the bus clears the intersection (phase extension) or advance the start of the green for the phase serving the buses (phase advance) (Skabardonis, 2000). TSP is granted subject to the safety constraints for pedestrians and vehicles, and the schedule adherence and occupancy of the transit vehicle. TSP improves bus travel times by 2% to 18% (USDOT, 2018), depending on the level of traffic volumes, TSP control algorithm and the accuracy of bus arrival time at the intersection. Simulation results show that TSP reduces the emissions of transit vehicles by 14% (Alam, 2014). Recent TSP systems detect the presence of pedestrians and bicycles at the intersection and adjust the signal timings to facilitate their movement.

Traffic signal control (Strategy 3.2): Traffic signals are the predominant form of control for arterial streets and grid networks. Traffic signals operate under specific timing plans (cycle length, and green times) to provide the right of way to conflicting traffic movements. Most of the existing signal systems use fixed time timing plans prepared off-line based on historical data on traffic demand. These plans are typically implemented by time of day (TOD), e.g., am, midday and pm peak periods to account for the variability of traffic flow, and updated every three years. On arterials, traffic signals are coordinated under a common cycle length to provide progression for major traffic movements. Optimization of signal timing plans is a highly cost-effective measure. The findings of California's Fuel Efficient Traffic Signal Management (FETSIM) program indicate that signal timing optimization of over 12,000 signalized intersections resulted in 14% reduction in delays and stops on the average; fuel consumption and emissions were cut by 8 % (Skabardonis, 1994). Several other studies nationwide reported reduction in fuel consumption and emissions between 5 and 15 % (Lawrence, 2015).

Traffic Responsive and Adaptive Traffic Signal Control: Fixed-time plans, however, cannot deal with the variability of traffic patterns throughout the day, and they become outdated because of the traffic growth and changes in traffic patterns. Also, "ageing" of timing plans degrades their traffic performance by 2-4% per year. Several control systems have been developed and implemented that adjust the signal settings at short time intervals based on data from detectors located on each intersection approach (Stevanovic, 2010). Findings from field and simulation evaluation studies indicate that these systems reduce fuel use and emissions by about 15% compared to fixed time plans under traffic conditions of high variability of traffic volumes (FHWA, 2017).

Ramp metering (Strategy 3.3): Traffic signals installed on freeway on-ramps control the frequency at which vehicles enter the freeway mainline. Ramp metering preserves the freeway mainline capacity, reduces mainline delay, and improves freeway travel time reliability. Eliminating the stop-and-go conditions due to congestion reduces emissions and fuel consumption. Environmental impacts are typically reported as total amount saved. For example, the Minnesota ramp

metering evaluation reported savings of 1,161 tons of carbon monoxide (CO) and Hydrocarbon (HC) pollutants saved but no % reductions in emissions were reported (Cambridge Systematics, 2001). Other studies report benefits of 12 to 17% reductions in emissions and travel times (USDOT, 2018). Safety benefits include reduction in the number of crashes because metering breaks up the platoons of on-ramp vehicles entering the freeway and competing for the same limited gaps in traffic (FHWA, 2014).

Ramp metering potential adverse operational impacts include a) spillback of the on-ramp traffic to the adjacent urban street networks, and b) increase in fuel consumption and emissions of on-ramp traffic, especially for a significant proportion of trucks in the traffic stream. Recently, control strategies that coordinate ramp meters with the signal control of adjacent traffic signals have been developed and tested to mitigate the spillovers. Also, ramp metering involves equity issues discussed in the companion paper.

Variable Speed Limits (Speed Harmonization) (Strategy 3.4): Use of signs to recommend travel speeds based on real-time sensor data on traffic conditions. Variable speed limits (VSL) can be regulatory or advisory. VSL are implemented in several States: Florida, Minnesota, Oregon, Virginia and Washington (FHWA, 2017). The objective of VSL is to smooth the sudden changes in travel speed and reduce the occurrence of shock waves due to congestion induced events (incidents, crashes, or adverse weather). Benefits include reduction in crashes, improvements in travel time reliability, and delay of the onset of congestion. Simulation results indicate that VSL reduce fuel consumption and emissions by 12 to 20% under congested conditions (Wang, 2006, Zhang, 2016).

Queue Warning Systems (QWS) (Strategy 3.9): Typically used in conjunction with variable speed limits to inform drivers of downstream stop-and-go traffic caused by incidents, work zones or facility locations with limited sight distance restricted by vertical grades, horizontal curves, or poor illumination. Several case studies indicate that QWS are effective in reducing the number and severity of rear-end accidents (FHWA, 2014).

Integrated Corridor Management (ICM): Coordinated management of urban networks with adjacent highway facilities (e.g., nearby parallel freeways), that comprise travel corridors under inter-agency data-sharing agreements (Cronin et al, 2010). ICM includes a combination of most of the operational strategies reviewed in this paper (strategies 3.1 through 3.12). Examples include system wide coordination of arterial traffic signals with adjacent on ramp meters controlling the freeway entrances to minimize the total system delay, traffic diversion to adjacent arterials in case of freeway lane closures due to incidents, and travel time information on several modes to facilitate real-time route choice (e.g., private auto, commuter rail, bus rapid transit). ICM implementations employ

automated decision support systems (DSS) to analyze the data received and suggest appropriate control actions to the system managers. Evaluations of the I-15 ICM in San Diego (Cambridge Systematics, 2016) and I-80 in the bay Area (System Metrics Group, 2019) indicated travel time improvements and reduction of accidents. Impacts on emissions and fuel consumption were not quantified. The latest FHWA report does not quantify the improvements other than total hours of travel time savings (FHWA, 2019).

Traffic Incident Management (Strategy 3.10): Combinations of procedures and tools for early detection, verification, response and removal of incidents on the highway facilities (i.e., accidents, disabled vehicles, etc.), so that normal traffic operations recover as quickly as possible. Agencies employ roving patrols that detect and respond to incidents. In California the Freeway Service Patrol (FSP) program operates on 1,800 centerline miles of most congested freeway segments. The benefits in terms of reduction in delays, fuel consumption, and emissions are calculated from the Freeway Service Patrol Evaluation (FSPE) analytical model using field data on incident characteristics and traffic volumes (Mauch, 2013). The findings indicate that the program is cost effective with estimated average emission reductions of 2-4% based on 2010EMFAC model emission factors (CARB, 2010). The FSPE model update in 2020 will include the latest MFAC factors. Similar findings on the effectiveness of FSP were found in other implementations using emission factors for European conditions (Kopelias, 2013).

2.1.3 Geometric Strategies

Dynamic Lane Control (Strategy 3.5): Dynamic allocation of specific travel lanes upstream of a freeway interchange (merging, diverging, and weaving), to accommodate surges in traffic demand from entering roadways. Dynamic merge control can be a permanent application at known bottlenecks, or it can be used temporarily for special events or until a downstream roadway is widened. Also, agencies may reallocate lanes at peak periods through the use of moving barriers. Results from case studies show 11% reduction on travel times with higher benefits during lane closures and work zones (USDOT, 2018).

Temporal Shoulder Use-Freeways (Strategy 3.6): This strategy allows traffic (or only transit vehicles in some locations) to use the shoulder temporarily at freeway bottleneck locations. This increases the available capacity and helps reduce congestion. The implementation of shoulder use depends on the prevailing conditions (shoulders free of disabled vehicles or other obstructions) and the design characteristics of the facility. Benefits reported range from 4% to 11% in travel times (USDOT, 2018). Higher benefits are predicted in the case of incidents under congested conditions (Margiotta, 2014).

Managed Lanes (Strategy 1.7 and 3.7): Strategies that regulate the access to specific freeway lanes subject to vehicle type, vehicle occupancy and pricing. Truck lane restrictions prohibit the use of one or more designated lanes of a highway by trucks. Lane restrictions can be designated on a 24-hour basis or only during the peak periods. The most common reasons for implementing truck lane restrictions include improving highway operations, reducing crashes, pavement and structural considerations, and construction work zone restrictions.

High occupancy vehicle lanes (HOV) are reserved for motorists with a minimum number of vehicles (typically two or three passengers per vehicle). HOV lanes may operate during the peak periods or 24-hours. High occupancy toll lanes (HOT) permit single occupant vehicles to use HOV lanes after paying a toll, essentially utilizing the spare capacity of the HOV lanes. Express lanes (toll lanes) are facilities that can be used by all vehicles that pay the entrance toll. The amount of toll depends on the vehicle occupancy, travel distance and congestion level. On congested freeways vehicles on HOV lanes produce 10% to 35% less emissions than vehicles traveling on general purpose lanes. The emission reductions improvements are negligible on uncongested freeways (Boriboonsomsin, 2007). A simulation evaluation of managed lanes implementation along a section of freeway I-85 in Orlando Florida showed a reduction of emissions on the limited access facility. However, several factors are critical to the performance of managed lanes, especially the ingress, egress locations and the subsequent weaving areas (Senna, 2014). Case studies on the conversion of HOV to HOT lanes, and operation of Express lanes indicate that these strategies significantly improve the average travel time and travel time variability at the expense of higher VMT which results in higher emissions (USDOT, 2018, Sullivan, 2016).

Complete Streets (Strategies 3.12, 4-3-4.6): "A complete street is a transportation facility that is planned, designed, operated, and maintained to provide safe mobility for all users, including bicyclists, pedestrians, transit vehicles, truckers, and motorists, appropriate to the function and context of the facility." (Caltrans, 2010). Implementation of complete streets measures (often referred to as "road diet" - *strategy 4.4)* involves narrowing or reduction of travel lanes for vehicles, provision of bicycle lanes, pedestrian refuge islands, and speed reduction through signage and control. Also, depending on the level of pedestrian activity and the availability of available road space, private vehicles may be prohibited to enter a street network (*Car-free zones-Strategy 4.3).*

Designs related to public transit *(strategy 3.12)* include exclusive bus lanes on arterials, and street designs that facilitate transit movements (e.g., bus bays and bus bulbs to facilitate safe loading, and reduce conflicts with other vehicles and on-street parking management to ensure the availability of adequate curb space for buses). These changes are often coordinated with transit service and control

improvements (e.g., bus rapid transit, higher frequency, real-time transit information and timed transfer centers).

The findings from twenty four case studies on road diet/complete streets (FHWA, 2015) indicate reduction to traffic volumes in the study area, no changes in vehicle travel times, and improved travel conditions for bicyclists and pedestrians. Findings of case studies suggest that road diet reduces VMT and accident.

2.2 Emerging Technologies

As computer and communication technologies continue to improve, new transportation applications are being developed and tested for improving mobility and safety. These include driver assistance systems for safety, advanced detection devices, new ways for storing, processing and analyzing data from multiple sources, and vehicle communication and automation systems.

Connected Vehicles (CVs) refer to the ability of vehicles of all types (passenger cars, trucks, buses) to communicate wirelessly with other vehicles (V2V), the roadway infrastructure (V2I), such as traffic signals, and other road users (e.g., pedestrians, bicyclists) (V2X) to support a range of safety, mobility and environmental applications (ITS JPO, 2017). The information on each vehicle's position, speed and direction in real-time means that each vehicle becomes a sensor so the traffic demand at the vehicle's trajectory level is known. Furthermore, the traffic signal phase and timing (SPaT) is known through V2I. An ECO driving advisory prototype system was developed and field demonstrated that provides the recommended speed to vehicles to clear the intersection without stopping. Results from field tests indicate savings of 14% in fuel consumption and emissions (Hia et al, 2012, Skabardonis, 2013). The V2X connectivity allows for developing control strategies for all road users. An example is the Multimodal Intelligent Traffic Signal System (MMITSS) (Head, 2016), that provides efficient control for all users at the signalized intersection: private vehicles, buses, freight vehicles, emergency vehicles, bicycles and pedestrians (Zhang and al, 2016). The V2V communication permits the vehicles to operate under cooperative adaptive cruise control (CACC) which allows travel in platoons with shorter headways. This increases the lane capacity on freeways, increasing saturation flow and reducing start up lost times at signalized intersections.

Deployment of CVs permits the development of innovative control strategies. Examples include queue spillback avoidance, control of congested grid networks and dynamic lane allocation (Skabardonis et al, 2013). The queue spillback avoidance strategy detects a presence of queue spillback at an intersection approach and determines the signal settings to prevent spillbacks from backing up the upstream intersection and avoid gridlock in grid networks. The dynamic

lane grouping (DLG) control strategy changes the lane utilization at the signalized intersection approach to accommodate spatial variations in traffic demands based on real-time origin-destination information from CV data.

The AERIS Research Program (US DOT, 2016) sponsored several studies to model and analyze connected vehicle applications to estimate the potential environmental impacts. The findings of these extensive modeling efforts are summarized in Table 2.1. In general, the AERIS applications showed that CVs reduced fuel consumption and emissions by 2% to 19% over conventional congestion management strategies. Additional findings also showed that optimizing for minimum fuel and emissions does not always minimize travel times, as it was discussed is the case for routing strategies.

Vehicle automation (VA) is a technology actively pursued by most vehicle manufacturers and high technology companies. The concept of AV is that completely self-driven vehicles will be able to drive in all operating environments. Currently several levels of automation have been established from level 1 (partial automation, active driver engagement, lane keeping and following distance) to level 4 (complete automation with no driver intervention). Automated vehicles may be completely autonomous, self-driven based on safety operating rules set by the automobile manufacturers, or connected with other vehicles. This section is concerned with the impacts of automation to the transportation system, assuming complete connectivity of automated vehicles (CAVs).

Figure 2.4 is a conceptual representation of the impacts for existing and emerging transportation technologies to mobility, safety, and air quality. The main message from this Figure is the potential relative impacts of each technology to the performance metrics. ATDM strategies offer modest improvements compared to existing strategies. Implementation of CAVs may drastically increase the capacity on freeways (from 2,000 veh/hr/lane to 6,000 veh/hr/lane). Accidents and could be reduced by 90%, and emissions may be cut by more than 60%. (Nowakowski and Shladover, 2010). It is important to note that the benefits depend on the penetration rate of CAVs as well as the characteristics of the communication system. The environmental, mobility, and safety benefits shown assume 100% penetration rate, which may take a long time period to be realized. Throughout this transition period, the transportation network will operate under a mixture of CAVs and manually driven vehicles. This affects the level of benefits and will also require strategies for efficient management of the incompatible traffic streams.

Table 2.1 Summary of AERIS Modeling Results (US DOT, 2016)

Application	Modeling Results

Eco-approach and Departure at Signalized Intersections	• The application provided 5-10% fuel reduction benefits for an uncoordinated corridor.
	• For a coordinated corridor, the application provided up to 13% fuel reduction benefits.
	   o 8% of the benefits were attributable to signal coordination.
	   o 5% attributable to the application.

Eco-Traffic Signal Timing	• When applied to a signalized corridor that was fairly well optimized, the application provided an additional 5% fuel reduction benefit at full connected vehicle penetration.
Eco-traffic Signal Priority	• The eco-transit signal priority application provided up to 2% fuel reduction benefits for transit vehicles. • The eco-freight signal priority application provided up to 4% fuel reduction benefits for freight vehicles.
Connected Eco-Driving	• When implemented along a signalized corridor, the application provided up to 2% field reduction befits at full connected vehicle penetration. • The application provided up to 2% dis-benefit in mobility (e.g. travel time) due to smoother and slower accelerations to meet environmental optimums.
Combined Eco-Signal Operations Modeling	• Together the Eco-Signal Operations application provided up to 11% improvement in CO_2 and fuel consumption reductions at full connected vehicle penetration.
Eco-Speed Harmonization	• The application provided up to 4.5% fuel reduction benefits for a freeway corridor. It assisted in maintaining the flow of traffic, reducing unnecessary stops and starts, and maintaining consistent speeds near bottleneck another disturbance area.
Eco-Cooperative Adaptive Cruise Control (eco CACC)	• Eco-CACC provided up to 19% fuel savings on a real-world freeway. • Vehicles using a dedicated "eco-lane" experienced 7% more fuel savings when compared to vehicles in the general lanes. • Eco-CACC has the potential to provide up to 42% travel time savings for all vehicles.

Combined Eco-Lanes Modeling	• Together the Eco-Lanes applications provided up to 22% fuel savings on a real-world freeway corridor for all vehicles. • Vehicles using the dedicated "eco-lane" experienced 2% more fuel savings when compared to vehicles in the general traffic lanes. • The scenario provided up to 33% travel time savings for all vehicles.
Low Emissions Zones	• A Low Emissions Zone modeled in the Phoenix Metropolitan Area results in up to 4.5% reduction in fuel consumption when both eco-vehicle incentives and transit incentives were offered. • The modeling indicated that the Low Emissions Zone has the potential to reduce vehicle miles traveled by up to 2.5% and increase by up to 20% in the Low Emissions Zones.

The impacts of CAVs may be far-reaching on several levels that are not captured in Figure 2.4. They entail changes on network design and operational performance, travel demand and behavior (mode choice, departure time choice, route choice), travel mode (vehicle ownership, new modes, shared services), and lifestyle choices (residential location, activities) (Peeta, 2017). The availability of share ride and car sharing fleets is likely to increase with CAVs, which can serve a wide range of users and destinations on-demand. This may significantly affect the demands on existing transportation networks, at a potential significant increase in VMT (Walker, 2017).
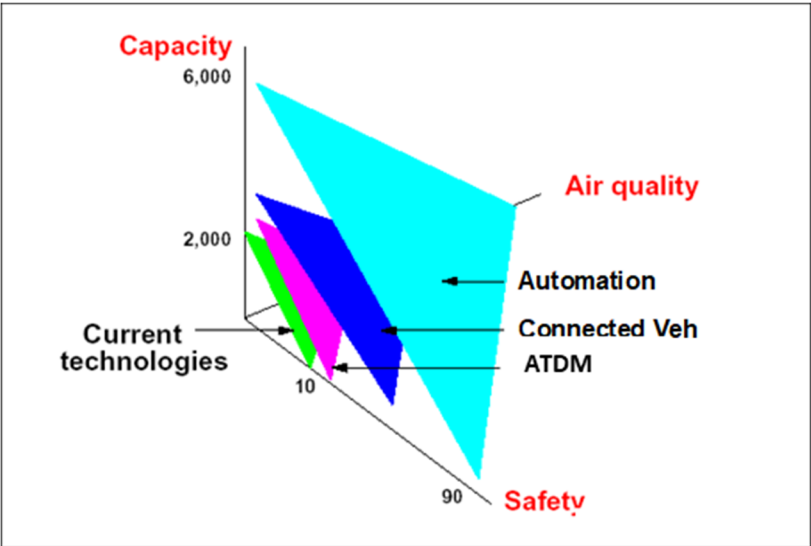

Figure 2.4 Potential Impacts of Transportation Technologies

CAVs operating under automated longitudinal and lateral control will provide precise positioning through travel and could lead to revised design standards regarding width (narrower lanes) and other design elements of highway design. The implementation of narrower travel lanes requires 100 % penetration rate for CAVs and initially can be tested on automated fleets (trucks and buses). Also, CAVs can potentially travel through intersections through a "time slot" control approach that allocates to the right of way without the need for traffic lights.

Fully automated vehicles are not currently operational on public highway facilities. As a result, their environmental impacts are based on modeling and simulation studies that involve assumptions on driver behavior and vehicle characteristics. Recent reviews (Caltrans, 2018, Kopelias 2019) show several studies in progress with limited results. The uncertainty of CAVs' impacts on energy also stems from the changes in VMT due to increased capacity, empty vehicle relation travel and new travel (Rodier, 2018). The findings from several studies sponsored by the Advanced Research Projects Agency-Energy (ARPA-E) indicate that the variation in environmental impacts due to CAV deployment is up to 50% depending on the scenarios of congestion reduction strategies with CAVs, increase in travel speeds, vehicle characteristics and VMT increase (USDOE, 2016).

2.3 Interviews

Interviews were conducted with five state, and three local and regional public agency staff in California, who have been involved in the planning, design, implementation, operation and evaluation of innovative congestion management strategies. Also, interviews were held with private consultants and academics and FHWA research staff. A total of eleven interviews were conducted by phone and in person and lasted on average one hour each, during the months of July and August, 2019. The main issues discussed during the interviews included:

- Congestion management strategies

- Measures of Effectiveness

- Role of New Technologies

Management Strategies

Most of the experts interviewed have direct experience with development and implementation of freeway congestion management strategies. The following strategies appear to be of the highest interest:

- Dynamic geometric strategies are considered highly effective on congested freeways. Examples include temporal lane addition via moving barriers during peak periods and temporal shoulder use during incidents or congested conditions at bottlenecks. These measures increase temporarily the capacity without the high cost of construction of adding new travel lanes.

- The most effective strategy from the menu of strategies in the ICM project on I-15 is the express lane with variable pricing depending on congestion and the easy access of express buses to the managed facility. The strategy improves the average travel time and travel time reliability and contributes to modal shifts to transit, which results in VMT reduction.

- Benefits of ICM incident management depends on the availability of parallel highway facilities to divert traffic during incidents. This strategy may be more effective in I-210 corridor, Los Angeles compared to the I-80 Bay Area because of more alternative routes on the Bay Area urban networks. FSP is an effective incident management strategy that operates on most California freeways.

- Signal control improvements along arterials is a very effective strategy. Improvements range from signal coordination to facilitate progression to advanced control algorithms that respond to the changes in traffic patterns. The assessment of effectiveness is based on a Caltrans sketch planning tool Traffic Light Synchronization Program (TLSP) that is likely to underestimate the benefits.

Performance Measures

State and local agency staff reported that the VMT reduction is the primary MOE in California. However, a VMT estimation framework is not currently available at Caltrans and other local agencies to account for the latent demand from operational improvements at the local and/or the regional level. There is a need to develop a reliable and accurate tool to calculate VMT and a multimodal optimization tool for developing GHG reduction and VMT strategies.

In operational studies (e.g., ramp metering) environmental MOEs are not typically reported. Emphasis is given to travel time savings (travel time and travel time reliability).

Currently, operating agencies calculate the environmental benefits using sketch planning tools typically provided by FHWA and State DOTs, e.g., FHWA Infrastructure Carbon Estimator (FHWA, 2014), Caltrans CAL B/C model, EMFAC factors, MOSAIC by Oregon DOT (Oregon DOT, 2014), Future Improvement Examination Technique (FIXiT) in Texas (Lasley, 2017). The experts recognize that currently a reliable method to estimate emissions and the % changes due to strategies is not available. Often the total amount of pollutants is reported. Interviewees recommended a detailed field study at a high volume facility (e.g., San Francisco Oakland Bay Bridge) to measure pollutant emissions "before" and "after" the implementation of traffic management improvements.

New Technologies

Transportation agencies conduct several studies at various time spaces (e.g., a 30 year transportation plan, a five year corridor investment study, etc.). Accounting in these studies for the impacts of emerging applications on the transportation network and traveler behavior is essential, but challenging (Zhu et al, 2018). The characteristics of CAVs are not yet determined, and there is no empirical evidence on their impacts to the transportation system until tested, yet implementation is projected. Critical issues to be addressed include:

- What values of link capacity should be assumed in developing 30 year transportation and land use plans given the presence of CAVs, and the changes in penetration rate over time?

- How to incorporate "smart cities" approaches in transportation plans, including new travel modes (ride-sharing), connectivity of travel modes and travelers, and lifestyle choices (residential location, activities)?

What are the driving cycles and operational characteristics of CAVs at different facilities in order to derive estimates of their environmental impacts? What are the driving cycles for connected vehicles?

CHAPTER 3

CONCLUSIONS

3.1 Synthesis of Literature Findings

The congestion management strategies described in this white paper typically can reduce GHG emissions in the range of 5% to 15%. Greater benefits may be achieved when a combination of measures are implemented as currently pursued by the ICM program.   The amount of benefits depends on the type of improvements, traffic patterns, and driver and vehicle characteristics (e.g., lower benefits are expected with the prevalence of electric and hybrid vehicles on the network). Also, a high % of emissions reduction does not necessarily indicate a high amount of pollutants saved that is used in the project's benefit-cost analysis.

Fuel consumption and emissions estimates in congestion management projects are typically derived from mobility related MOEs (travel time, speed, stops), and VMT based on analysis procedures that may not accurately calculate these impacts. Furthermore, VMT reduction is becoming the primary MOE for California operating agencies. There is no multimodal optimization tool to minimize mobility related MOEs, emissions, and VMT.

Operational strategies consisting of temporal capacity additions (re-allocation of travel lanes, temporal shoulder use) are cost effective to congestion and safety problems, compared to capacity expansion projects (new highways or additional lanes).   More importantly, the temporal lane addition does not generate induced demand, which typically occurs after permanent lane additions. However, their environmental impacts have not been documented. This is also the case for managed lanes involving lane use restrictions.

A significant amount of research focuses on the impacts of CAVs. Simulation results indicate that CAVs operating under existing traffic management strategies may further reduce fuel and emissions by 2 to 22% (USDOT, 2016). There is limited empirical evidence on the behavior and impacts of CAVs on traffic performance. Currently, there are two CAV pilot programs in urban networks (Tampa Florida and New York City) where a wide range of traffic applications are currently being tested with connected vehicles (ITS JPO, 2017). Further uncertainties in the predictions are due to behavioral changes that may lead to VMT increases.

3.2 Major Research Gaps

The review of the literature and the discussions with experts identifies a number of research gaps related to congestion reduction strategies and their environmental impacts. Research is needed on technology required for the implementation of

strategies, analysis tools for assessing their effectiveness and understanding of the connection between environment, mobility, and safety performance of any congestion reduction programs.

Technology Requirements

The deployment of ATDM strategies in urban networks requires significant infrastructure investments including surveillance devices on each intersection approach and travel lane, and communication with the transportation management center (TMC). There is a need for comprehensive evaluation studies to determine the type and function of the infrastructure required for ATDM deployment and the associated lifetime costs. The issues to be address include, but are not limited to:

- Emerging non-intrusive technologies (video, mobile sources, drone devices) to provide information on traffic conditions

- Pedestrian and bicycle detection systems at signalized intersections. Upgrading Traffic signal controllers and interconnection fiber communications or other interconnects between signals may be required to support adaptive operations on an arterial corridor.

- The implementation of dynamic facility management measures requires installation of overhead lane control signs approximately half a mile apart.

Looking ahead, the deployment of CAVs will require highly secure wireless communications, and data management:

- Safety-related systems in the CAV environment will likely be based on Dedicated Short-Range Communications (DSRC). Non-safety applications may be based on different types of wireless technology (ITS JPO and ITE, 2017). DSRC is an open-source wireless communication protocol, with low latency and limited interference intended for highly secure, high-speed wireless communication between vehicles and infrastructure. Wide deployment of DSRC communications for V2I in the transportation infrastructure is challenging because of the substantial investment without a dedicated government funding source.

- Operation of CAVs on highway facilities will generate a large amount of data that existing TMCs do not have the capacity to store, process and analyze. There is a need for developing a national framework that defines the process involved with the collection and sharing of data with CAVs, and creates tools and standards, plus development of tools to support these functions (TRB, 2016).

Estimation of Fuel Consumption and Emissions

Earlier analysis tools for estimating fuel consumption and emissions, e.g., MOBILE 6 (Barth, 1999) use emission factors for different travel speed. Modal emissions

models, such as the MOVES model (Bibake, 2019), consider the time spent in each driving mode using bins categorized by speed, and acceleration. The time spent in each operating bin is obtained from trajectories generated by traffic simulation models. Recently, a new model *Autonomie,* developed by Argonne National Laboratory (Islam, 2017) calculates each vehicle's fuel consumption and emissions based on details such as engine speed and gear position at every timestamp, and second-by-second trajectory data generated by microscopic simulation models. The high-resolution trajectory data are essential to precisely model the effect of speed fluctuations and stop-and-go waves in congested conditions on fuel consumption and emissions.

Model-based fuel and emission estimates even at a high time resolution may not be accurate, because the trajectories generated by the existing state-of-the art simulation tools do not necessarily replicate the real world. Microsimulation models are calibrated to reproduce performance at the macroscopic level (bottleneck capacity, link travel time), not individual vehicle performance. There is a need to develop methodologies that estimate emissions based on real-world vehicle trajectories. Currently, new technologies and algorithms allow the collection of trajectory data in the field and clustering at various traffic states.

Traffic Analysis Tools

Existing traffic analysis tools available to the transportation agencies are not well suited for evaluating emerging technology applications due to their inability to incorporate vehicle connectivity as well as automation, as these tools were designed and calibrated based on data from human driven vehicles in the traffic stream that may no longer hold in a connected environment. Until new tools become available, calibrated and validated with field data, agencies need specific guidance on the application of existing tools for CAVs and their limitations. Some of the critical shortcomings of existing modeling and simulation tools include:

- *Simulation of CAV equipment*: Limitations in modeling CAV characteristics makes it difficult to evaluate the anticipated effects of various connected vehicle scenarios (e.g., equipment failures, communication latency issues, typical loads and resource demands). This makes it difficult to assess the effectiveness of alternative CAV equipment configurations for a particular application. Currently, a fixed parameter is assumed for latency based on the communication equipment type.

- *Limitations in modeling driver behavior:* Existing simulation tools model driver behavior based on car-following, lane-changing and queue discharge algorithms. These algorithms are currently designed to model human behavior, and have been calibrated based on vehicle trajectories of human driven

vehicles.   This may be an inaccurate representation of how vehicles will operate when CV technologies and various levels of automation become prevalent (Kan, 2016). Examples include car following in mixed traffic of manual and platoon CAV vehicles, minimum headways accepted by travelers, lane changing rules and safety margins under automated driving.

- *Limitations in modeling driver responses to CAV applications:* Several responses including driver acknowledgement, comprehension, and compliance are not currently explicitly modeled in the existing analysis tools. Often a fixed compliance rate parameter is used to model the driver reaction to most CAV applications. However driver response is not static; it depends on the particular application, reliability of information, trip route, and perceived position or speed improvement.

- *Limitations in modeling CAV applications:* CAVs offer the opportunity for implementing new mobility strategies. However, the simulation of such applications in general is time consuming and requires custom code and logic in the model added by the analyst. In a recent FHWA study, it was found that 30% of the applications sponsored by FHWA in the CV pilot deployment program cannot be analyzed with the existing modeling tools (Alexiadis, 2017).

Framework for Environmental Assessment of Congestion Management Strategies

There is a need to develop a framework for evaluating the performance of congestion management projects with respect to greenhouse gas and criteria pollutant emissions and equity, especially in light of the interactions of traffic flow improvements and emissions (Figure 1.1). The traditional four-step travel demand models are ill-equipped to capture induced demand because of the lack of feedback to trip generation (including vehicle ownership) and land use.

The proposed framework is an integrated modeling approach with advanced features in order to understand the supply and demand implications for alternative investments. These features should include a land use model that is sensitive to changes in transportation network conditions, an activity-based travel demand model and a dynamic traffic assignment. The framework will be developed and tested on sample real-world projects to verify that it reliably assesses the effectiveness of innovative projects, including ATDM strategies involving multimodal strategies on freeways and surface streets, and ride-sharing services in city centers that raise conflicts with travel through neighborhoods, and curb management conflicts (Schaller, 2017). The application of the framework in "before" and "after" should be of sufficient length (one or two years) to obtain travel time reliability estimates and observation of demand shifts.

The framework should be able to present the impacts in a benefit-cost analysis to facilitate communication of the benefits of new technologies to decision-makers. Elected officials and agency leaders who must make decisions about whether to invest in development of new technologies need clear communication on what the new technologies can do, the expected timeframe for implementation, costs involved in implementation and operations, plus anticipated benefits. The communication regarding the benefits should be presented in a benefit-cost analysis comparing the existing operations, the system operations under existing technology with optimized conditions, and operations with the new technology. At the same time, the framework should address the equity impacts as have been presented in the companion paper.

Communicating the emerging implementation of CAV technology to elected officials and energy leaders presents several challenges given the wide availability of information from various sources on technology capabilities and impacts. Several agencies think that CAVs will mean the end of control devices that are required to install and maintain (e.g., traffic signals, stop signs). Although this may be a possible scenario in the future, is not likely to be implemented in the short term. There is a need for clear guidance to public agencies and the regulatory requirements regarding the technology.

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