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Development of Comprehensive Roadmap and Resource Guide Towards Congestion Reduction

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16. Abstract

Traffic congestion poses a significant challenge in the United States, affecting mobility, public health, and the environment. With national travel delays and fuel waste on the rise, there is an urgent need for a comprehensive approach to congestion mitigation. This research develops a congestion reduction roadmap, focusing on 12 key mitigation areas, including advanced traffic signal optimization, incident management, and multimodal transportation strategies. Through a combination of literature review, expert interviews, and case study analysis, the roadmap provides actionable steps for state and local agencies to manage congestion effectively. The framework addresses both short-term and long-term solutions, emphasizing technology integration and multimodal options to foster sustainable urban mobility and reduce congestion's economic and environmental impacts.

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Congestion Mitigation Area	Name	Affiliation
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	Adam Cohen	
Other Emerging Technologies	Yu Zhang	CUTR, USF
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Abbreviations and Acronyms

ADOT	Arizona Department of Transportation
AAM	Active Arterial Management
AAM	Advanced Air Mobility
ADAS	Advanced Driver Assistance Systems
ARC	Atlanta Regional Commission
ADA	Americans with Disability Act
AU	Autonomous Vehicles
AI	Artificial Intelligence
APTA	American Public Transportation Association
AR	Augmented Reality
ASCT	Adaptive Signal Control Technologies
ATC	Automated Train Control
ATCS	Adaptive Traffic Control System
ATM	Active Transportation Management
ATSPM	Automated Traffic Signal Performance Measures
AU	Augmented Reality
ALPR	Automated License Plate Recognition
AVL	Automatic Vehicle Locations
BART	Bay Area Rapid Transit
BRT	Bus Rapid Transit
BVLOS	Beyond Visual Line of Sight
CAV	Connected and Automated Vehicles
CBTC	Communication-Based Train Control
CCTV	Closed-Circuit Television
CHART	Coordinated Highways Action Response Team
ConFAVs	Connected Fully Autonomous Vehicles
CV	Connected Vehicles
CP	Congestion Pricing
CTR	Commute Trip Reduction
DLA	Dynamic Lane Assignment
DLT	Distributed Ledger Technology
DOT	Department of Transportation
DSRC	Dedicated Short-range Communication
DAR	Drive-Alone Trip
DMS	Dynamic Message Sign
EAV	Electric Autonomous Vehicles
ETC	Electronic Toll Collection
eVTOL	Electric Vertical Takeoff and Landing
EVP	Emergency Vehicle Preemption
FAA	Federal Aviation Administration
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration

FMS	Freeway Management System
FSP	Freight Signal Priority
HOV	High Occupancy Vehicle
HOT	High Occupancy Toll
HAR	Highway Advisory Radio
HCM	Highway Capacity Manual
HCS	Highway Capacity Software
GIS	Geographic Information Systems
GPS	Global Positioning System
GRTC	Greater Richmond Transit Company
ICM	Integrated Corridor Management
ICT	Information and Communication Technologies
IoE	Internet of Everything
IoT	Internet of Things
IR	Infrared
ITS	Intelligence Transportation Systems
LE	Law Enforcement
LTR	Leave Time Reward
MaaS	Mobility as a Service
MCAT	Manatee County Area Transit
MPO	Metropolitan Planning Organization
ML	Machine Learning
MDOT	Michigan Department of Transportation
MoDOT	Missouri Department of Transportation
NCHRP	National Cooperative Highway Research Program
OBU	On-Board Unit
PT	Public Transportation
P2P	Person to Person
RTD	Regional Transportation District
RFID	Radio Frequency Identification
SMN	Smart Mobility Network
SPaT	Signal Phasing and Timing
SWZ	Smart Work Zone
TDM	Transportation Demand Management
TDOT	Tennessee Department of Transportation
THEA	Tampa-Hillsborough Expressway Authority
TIM	Traffic Incident Management
TMC	Traffic Management Center
TSM&O	Transportation Systems Management and Operations
TSP	Transit Signal Priority

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Executive Summary

Traffic congestion is a pressing issue in the United States, leading to significant economic, environmental, and societal costs. Increased travel delays, fuel consumption, and vehicle emissions underscore the urgency of implementing effective congestion mitigation strategies. Although numerous documents on congestion mitigation exist and innovative technologies continue to emerge, a comprehensive roadmap and resource guide that fully integrates these advancements has been lacking. The primary objective of this report was to develop a comprehensive roadmap for congestion reduction, incorporating established strategies and emerging solutions across 12 key congestion mitigation areas to assist transportation agencies in alleviating congestion efficiently and sustainably.

Overview of Congestion and Its Impacts

Congestion is categorized into recurring and non-recurring types. Recurring congestion results from predictable factors such as bottlenecks and poor signal timing, while non-recurring congestion arises from unexpected incidents like crashes, work zones, adverse weather, and special events. Over the years, congestion-related costs have escalated, with annual travel delays rising from 5.1 billion hours in 2000 to 8.7 billion hours in 2019, and fuel waste increasing from 2.4 billion to 3.5 billion gallons in the same period. The economic impact has surged to $190 billion annually, with truck congestion alone costing $20 billion. The COVID-19 pandemic temporarily reduced these figures, but recent data indicates a rebound.

Key Congestion Mitigation Areas

This report presents a **strategic roadmap** covering **12 major congestion mitigation areas**, aimed at providing actionable solutions for transportation agencies:

1. **Smart and Advanced Signal Timing and Optimization Systems** – Real-time traffic management solutions that dynamically adjust signal timing to improve flow and reduce delays.
2. **Traffic Incident Management (TIM)** – Coordinated efforts among incident responding agencies to detect, respond to, and clear incidents quickly, minimizing disruptions.
3. **Transportation Systems Management and Operations (TSM&O)** – A proactive approach using intelligent transportation systems, integrated corridor management, and adaptive strategies.
4. **Multimodal Transportation** – Encouraging a seamless transition between transportation modes, such as walking, cycling, public transit, and personal vehicles.
5. **Shared Transport Systems** – Carpooling, bike-sharing, and ridesharing solutions aimed at reducing single-occupancy vehicle trips.
6. **Telecommuting and Flexible Work Hours** – Reducing peak-hour travel demand by enabling remote work and staggered scheduling.
7. **Smart Navigation Systems** – GPS-based, AI-driven applications that optimize travel routes to minimize congestion.
8. **Public Transportation Systems** – Expanding and enhancing bus, rail, and rapid transit services to provide viable alternatives to private vehicles.
9. **Congestion and Road Pricing** – Implementing tolls, congestion pricing, and demand-based pricing strategies to regulate traffic volume.

10. **Connected and Automated Vehicles (CAVs)** – Leveraging autonomous and connected vehicle technologies to optimize traffic efficiency.
11. **Advanced Transportation Technologies** – Innovations such as electric and high-speed rail, electric vertical takeoff and landing (eVTOL) aircraft, and hyperloop systems.
12. **Other Emerging Technologies** – Exploring futuristic solutions like maglev trains and smart infrastructure to enhance urban mobility.

Implementation and Impact

This congestion reduction roadmap provides a clear, strategic vision and actionable solutions for stakeholders working to address traffic congestion. Tailored for state and local transportation engineers, managers, practitioners, professionals, as well as researchers and students, it serves as an invaluable decision-making tool. The roadmap supports the development of effective congestion reduction strategies, prioritizes investments in efficient transportation systems and cutting-edge technologies, and guides the formulation of progressive, future-focused policies.

Focusing on practical implementation, the report details step-by-step recommendations for applying the roadmap and provides a comprehensive resource guide for stakeholders. By embracing these congestion mitigation strategies, agencies can make data-driven investments in effective transportation systems, leverage emerging technologies, and craft policies that foster sustainable, resilient urban mobility. Advocating for a multimodal, technology-integrated approach, the roadmap ensures that solutions are adaptable and scalable across a wide range of metropolitan environments, from smaller cities to major urban hubs.

Recommendations and Insights

The key findings from this research emphasize the urgent need for collaboration between transportation agencies, industry stakeholders, and policymakers to successfully implement congestion reduction strategies. As urban populations continue to expand, a proactive, integrated, and flexible approach to congestion mitigation will be crucial for creating safe, efficient, and sustainable transportation systems. This congestion reduction roadmap and resource guide developed from this project offers a clear, actionable framework and resources that support short-term, mid-term, and long-term planning, ensuring the development of smarter, more efficient and integrated transportation networks across the United States.

Chapter 1. Introduction

Congestion has been a growing issue across the United States (U.S.) (Schrank et al., 2021). It is characterized by the disruption of transportation networks and disturbs society in many ways that are beyond transportation systems. It can negatively affect people's health, quality of life, and the environment (e.g., pollution, noise, and stress) (Meyer, 1997). Nationally, travel delays have increased from 5.1 billion hours in 2000 to 8.7 billion hours in 2019, while the amount of fuel wasted has risen from 2.4 billion gallons in 2000 to 3.5 billion gallons in 2019. Similarly, the excess greenhouse gas emissions have escalated from 25 million tons to 36 million tons during the same period. Similarly, the cost of congestion more than doubled from 2000 to 2019 from 77 billion dollars to 190 billion dollars. Truck congestion costs also grew to 20 billion dollars from 7 billion dollars during the same period. Although these numbers were down during the year 2020 due the COVID-19 lockdowns and restrictions, the most recent data shows a rebound at the end of 2020 (Schrank et al., 2021). The occurrence of congestion also varies based on circumstances. Congestion issues fluctuate depending on the roadway types, geographic locations, and time of day. For example, different cities, counties, and metropolitan areas experience varying degrees of congestion.

Congestion issues can be classified into two main types: recurring and non-recurring. While recurring congestion can reflect issues related to balancing demand and supply, as well as demand management, non-recurring congestion is usually caused by various incidents, such as crashes, incidents, weather related events, or other special events. The various sources of congestion can be further classified as follows (see Figure 1 for more details):

- Recurring Congestion
    - Bottlenecks
    - Poor Signal Timing
- Non-Recurring Congestion
    - Traffic Incidents
    - Work Zones
    - Inclement Weather
    - Special Events

Other factors that affect traffic congestion comprise urban planning and land use, population growth, economic growth, road infrastructure, public transportation availability, and policy and regulation. Numerous traffic congestion mitigation strategies are available, which can be further subdivided into short-term and long-term strategies (Schrank et al., 2021; Meyer et al. 1989; Meyer, 1997; Litman, 2019). With technological advances, the list of those strategies has also expanded.

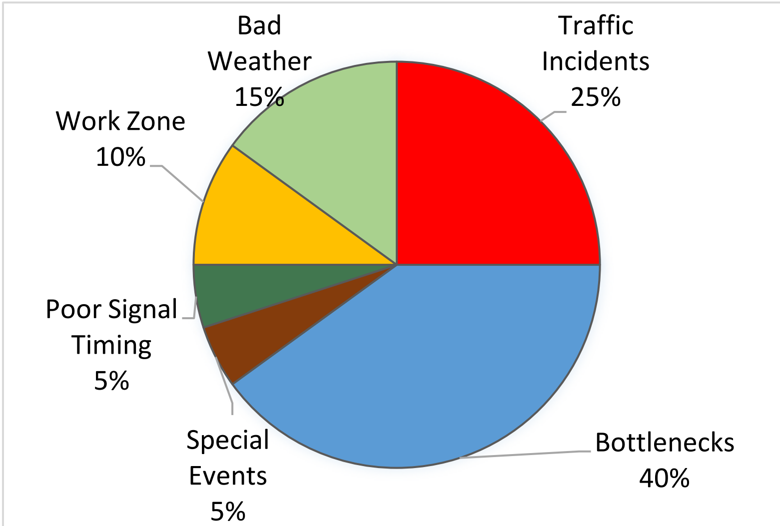


Figure 1. Sources of congestion.

Source: (FHWA, 2020b)

Although various documents on congestion mitigation are available and innovative technologies are emerging, a comprehensive roadmap and resource guide for reducing congestion has been lacking. The primary goal of this work was to develop a comprehensive roadmap for congestion reduction. The roadmap developed from this research incorporated combined solutions across 12 established and emerging congestion mitigation areas, as shown in Figure 2, to address traffic congestion problems faced by metropolitan areas of varying types (very large, large, medium, and small). The implementation of strategies and associated countermeasures in these 12 areas could potentially lead to a significant reduction in traffic congestion. This report aims to equip state departments of transportation (DOTs), local transportation agencies, and metropolitan planning organizations (MPOs) with a comprehensive roadmap and resource guide considering these key 12 congestion mitigation areas for proactively and effectively planning, investing in, designing, and implementing solutions and strategies to alleviate traffic congestion.

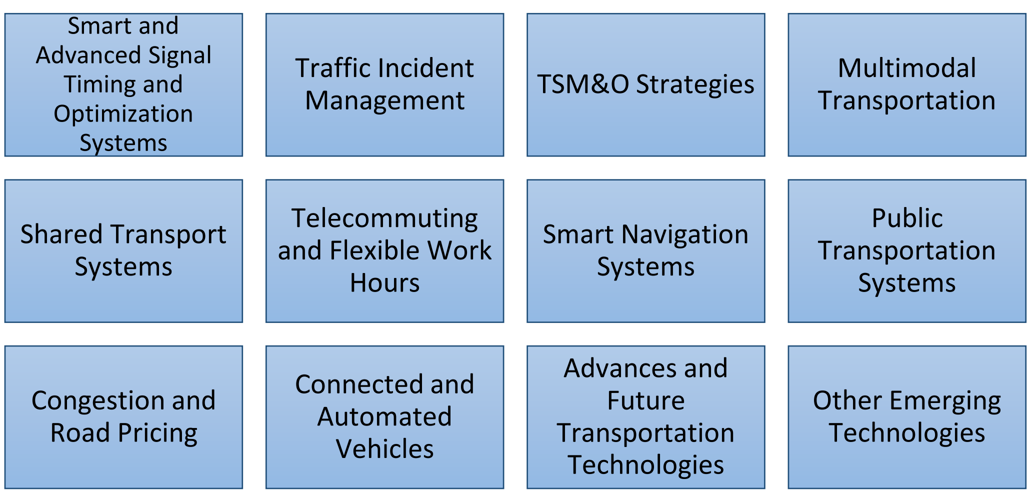


Figure 2. Major traffic congestion mitigation areas.

Description of Key Areas for Mitigating Congestion

A brief description of each of these 12 key congestion mitigation areas is provided below.

1. Smart and Advanced Signal Timing and Optimization Systems are traffic management systems and technologies that use real-time data and advanced algorithms to adjust signal timing at intersections, aiming to improve traffic flow, reduce congestion, and enhance overall transportation efficiency.
2. Traffic Incident Management incorporates coordinated efforts by various agencies and stakeholders to detect, respond to, and clear traffic incidents efficiently and safely. It aims to minimize disruptions, reduce congestion, and enhance safety on roadways through effective communication, coordination, and resource allocation.
3. Transportation Systems Management and Operations (TSM&O) Strategies are proactive measures and techniques implemented by transportation agencies to enhance the efficiency and performance of transportation networks, particularly in reducing traffic congestion. These strategies typically involve optimizing existing infrastructure, implementing intelligent transportation systems, managing traffic flow, and promoting alternative modes of transportation to alleviate congestion and improve overall mobility and safety.
4. Multimodal Transportation is a transportation system that integrates multiple modes of travel, such as cars, buses, trains, bicycles, and walking, within a single network or corridor. This approach aims to provide users with diverse transportation options and seamless connections between different modes, enhancing accessibility, efficiency, and sustainability in urban and regional transportation systems.
5. Shared Transport Systems utilize vehicles or transportation services by multiple users, often on a per-trip or subscription basis, rather than individual ownership. These systems include ridesharing, carpooling, bike-sharing, and shared mobility services. They promote resource efficiency, reduce congestion, and offer flexible and affordable transportation options for users.
6. Telecommuting and Flexible Work Hours refer to working remotely, often from home, using technology and allowing employees to adjust their schedules outside standard work hours (9:00 AM to 5:00 PM). Both strategies offer autonomy, work-life balance, and potential reductions in commuting-related congestion.
7. Smart Navigation Systems employ real-time data and algorithms to guide drivers through optimal routes, avoiding congested areas, and suggesting alternative paths. By optimizing traffic flow and reducing congestion hotspots, these systems enhance overall transportation efficiency and reduce travel time for users.
8. Public Transportation Systems are networks of buses, trains, and other shared transit options serving communities. By providing convenient, affordable alternatives to private car travel, they help reduce traffic congestion by accommodating more passengers per vehicle and encouraging modal shifts, thereby easing road congestion and improving overall mobility.
9. Congestion and Road Pricing charges motorists fees based on factors like time, distance, and congestion levels to manage traffic demand and reduce congestion. By discouraging unnecessary trips and encouraging alternative modes of transportation, these pricing strategies help optimize road capacity and alleviate congestion.
10. Connected and Automated Vehicles are advanced technologies to communicate with other vehicles and infrastructure, enabling coordinated traffic flow and efficient routing. By reducing human error,

optimizing driving patterns, and facilitating platooning, Connected and Automated Vehicles (CAVs) help alleviate congestion and improve overall traffic efficiency.

11. Advanced Transportation Technologies encompass innovations like CAVs, smart traffic management systems, electric vehicles (EVs), unmanned aerial vehicles (UAVs), high-speed rail, and electric vertical takeoff and landing (eVTOL) aircraft. By leveraging cutting-edge solutions, they optimize traffic flow, reduce congestion, and enhance transportation efficiency, contributing to improved urban mobility and greater sustainability.
12. Other Emerging Technologies include advanced eVTOL aircraft, hyperloop systems, maglev trains, and flying cars, which are still under development. These innovations offer promising solutions to future traffic congestion by providing faster, more efficient modes of transportation that can bypass traditional road networks, significantly enhancing urban mobility.

In addition to the roadmap, a resource guide has been created to assist transportation agencies, practitioners, researchers, and students interested in the topic. This roadmap and resource guide will serve as vital tools for long-term, mid-term, and short-term planning in congestion reduction, strategy implementation, infrastructure and technology investment, policy development, and legislation. They will offer a clear vision for transportation professionals and industries working towards effective congestion mitigation.

Research Objectives

The specific objectives of the project include:

- Conduct a comprehensive literature review on 12 major areas of traffic congestion mitigation and provide detailed documentation and findings.
- Conduct interviews with congestion management experts and representatives from transportation agencies, consulting firms, and technology industries to gather information and input on each of the 12 major areas.
- Develop a comprehensive roadmap supplemented with a resource guide.
- Provide state DOTs, local transportation agencies, and MPOs with a vision and actionable steps towards congestion reduction.

Organization of Report

The remainder of this report is structured as follows: Chapter 2 delves into a comprehensive literature review covering 12 major areas for reducing traffic congestion. In Chapter 3, the insights gleaned from interviews with experts and practitioners are summarized. Chapter 4 presents a congestion reduction roadmap, and a resource guide designed to tackle traffic congestion. Finally, Chapter 5 offers conclusions drawn from the findings and provides recommendations for future actions.

Chapter 2. Literature Review

The literature review provides insights gathered from previous research in 12 identified key areas for reducing traffic congestion. For each of these 12 key areas, the review aims to cover definitions, subareas, strategies, approaches, technologies, benefits, limitations, uncertainties, and interactions with other key areas. The sections presented in this chapter provide detailed findings from each area under review.

Smart and Advanced Signal Timing and Optimization Systems

This section contains a summary of the literature regarding smart and advanced signal timing and optimization systems. It provides a description of these systems and explores how they can effectively alleviate traffic congestion.

Definition and Subareas

Definition

Smart and advanced signal timing and optimization systems include adaptive traffic control systems and other smart signal systems. Adaptive traffic control systems (ATCSs) "adjust, in real time, signal timings based on the current traffic conditions, demand, and system capacity" (Stevanovic, 2010). ATCSs involve surveillance using loop detectors or video cameras, as well as communication between central and/or local controllers. With ATCSs, parameters such as split, offset, phase length, and phase sequences are dynamically adjusted through built-in algorithms to optimize coordinated traffic flow, reduce delays, and minimize the number of stops (Stevanovic, 2010; FDOT, 2016). In other words, ATCSs use programmed approaches to accommodate, stabilize, and smooth changing traffic patterns to reduce congestion (FHWA, 2017; Salem, Chen, & Salman, 2015).

Similarly, "smart" signals involve systematic monitoring of arterial road traffic signals. The system "automatically collects and processes data from traffic signal controllers at multiple intersections. It then creates performance measures, including information on the times and locations congestion occurs on a given road" (ITS, 2012).

Subareas

Subareas include adaptive traffic signals, system wide adaptive ramp metering, and smart signal systems.

Congestion Reduction Strategies, Conditions, and Approaches

ATCSs use data from sensors to decide the red and green statuses of lights at intersections, which helps to reduce delays and improve traffic flow on local roadways and highways (FHWA, 2017). The systems deal with temporal fluctuations that happen hourly, daily, weekly, and during unpredictable non-recurring congestion (FDOT, 2016; Stevanovic, 2010). Travel time reliability measures can help determine the corridors that frequently experience demand fluctuations and non-recurring congestion. Roadways close to land uses causing variable traffic flow, including events and sporting sites and large shopping centers, will likely gain from ATCSs. Advantages of ATCSs are usually noticeable when compared to (FDOT, 2016):

- Previously uncoordinated systems,
- Coordinated systems with outdated timings, and,
- Systems with variable non-recurring congestion.

The Florida Department of Transportation (FDOT) indicated that ATCSs "can continuously distribute green light time equitably for all traffic movements, improve travel time reliability by progressively moving vehicles through green signals, reduce congestion by creating smoother flow, and prolong the effectiveness of traffic signal timing" (FDOT, 2016). It is not appropriate to consider adaptive signals when the intersection is congested, and the signal timing is recent (FDOT, 2016). Although ATCSs can delay the start of saturation, they do not perform well under those circumstances (FDOT, 2016; Stevanovic, 2010). Thus, understanding when to utilize ATCSs is essential, and a decision flow chart illustrating this process is provided in Figure 3. In other words, "it is important to understand that it should not be expected that an ATCS deployment can totally resolve all traffic congestion issues. Instead, ATCSs could be considered as tools that can help to reduce traffic congestion by promoting the operational control and management of the transportation network" (Stevanovic, 2010). The major reasons why agencies implement an ATCS is available in Figure 4, which covers Advanced Signal Control Technology (ASCT) in general.

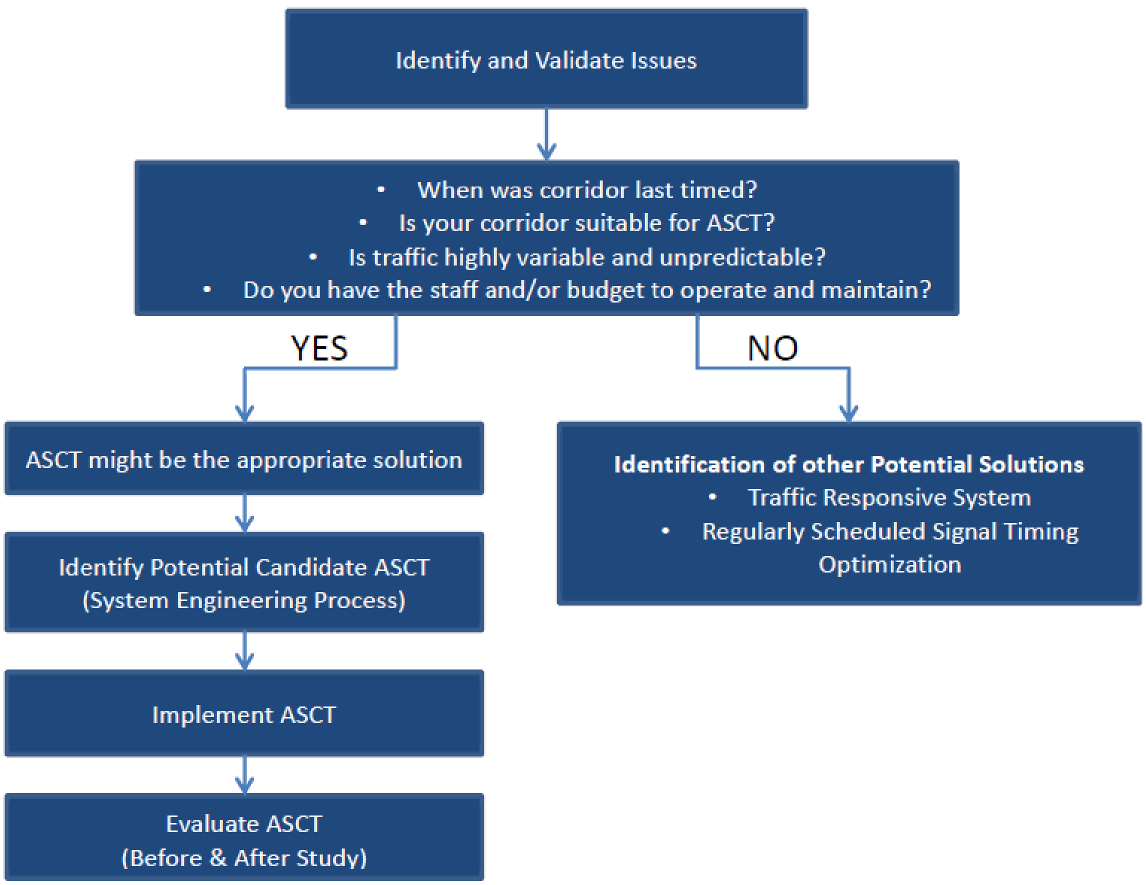


Figure 3. ATCS or ASCT decision flow chart.

Source: (FDOT, 2016)

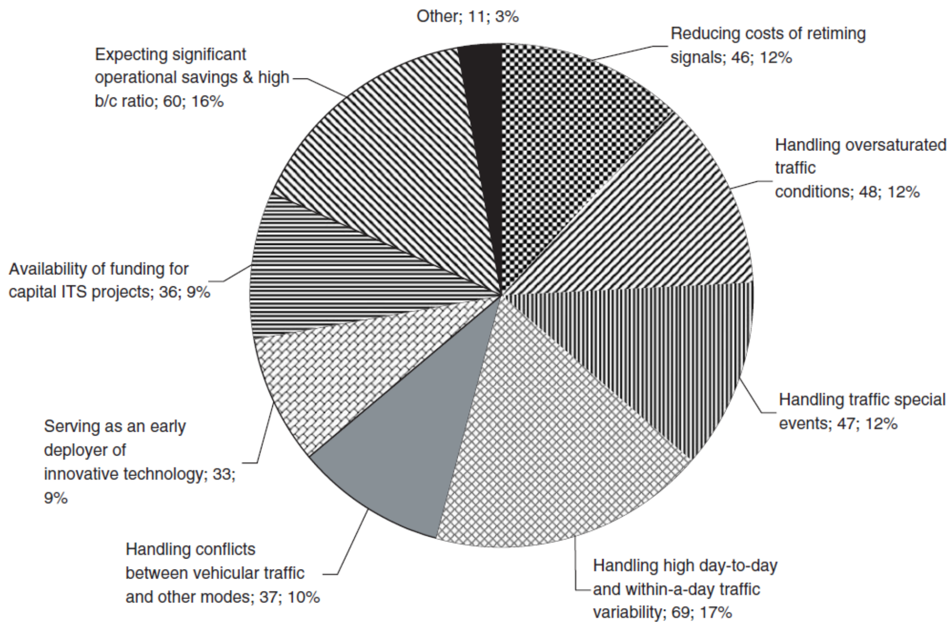


Figure 4. Major reasons for implementing an ATCS.

Source: (Stevanovic, 2010)

Information from smart signals can be used to assess the quality of signal timings and the overall system performance. For example, as part of the GreenWay project (Figure 5), FDOT plans to use sensor technology, smart parking technology with signal performance metrics (SPM), and signal control analytics and visualization among many other strategies. GreenWay will help FDOT manage over 1,000 traffic signals within the region and will support real time operation through a regional decision support system (DSS). The project will enable strategic planning for special events for all modes and users (FDOT, 2022a).

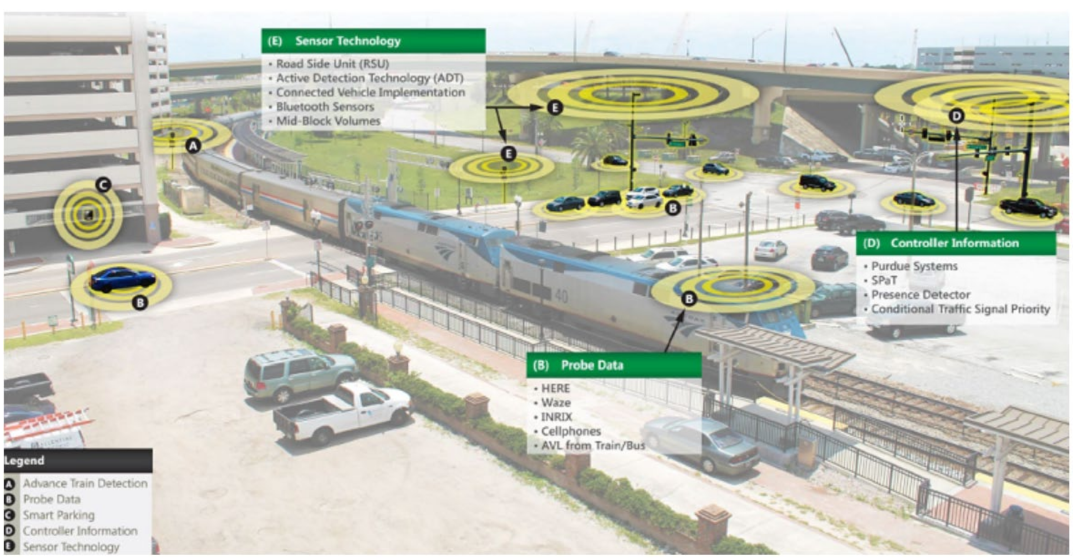


Figure 5. The FDOT GreenWay project.

Source: (FDOT, 2022a)

Advanced traffic management technologies, including adaptive traffic control and traffic analytics, have the potential to enhance safety and reduce congestion. These technologies facilitate the creation of smart intersections that can help solve many urban transportation issues with big and real-time data. Although the systems can accommodate growing populations, they need to be associated with other strategies for better results under those circumstances (Citron, 2019).

Current and Future Technologies

Some of the current technologies used in smart and advanced signal timing systems that will probably evolve in the future include:

- **Video and artificial intelligence (AI)** technology (Citron, 2019)
- **Sensors** (FHWA, 2017)**, IR sensors, and Wi-Fi technology** (Atta, Abbas, Khan, Ahmed, & Farooq, 2020)
- **Detection and communication technologies** (Stevanovic, 2010)
- **Radio Frequency Identification (RFID)** is a technology used to create wirelessly readable tags for animals or objects. RFID innovation can be used to alleviate traffic congestion and find blockages at any intersection of the street by utilizing RFID readers and labels as sensors. It can help to make the fixed and preset activity of traffic signals dynamic (Atta et al., 2020).
- **Internet of Things (IoT)** Technology, in which everything is connected, uses the internet of factors, the network of physical item devices, motors, homes and different gadgets that can be inserted in electronics, software, sensors, and network connectivity.

IoT = Physical Object + Controller; Sensor; Actuators + Internet

Smart and intelligent systems can reduce congestion through dynamic signal timings based on traffic density sensed with IoT-enabled sensors. These sensors, which enable the introduction of smart surroundings or self-conscious aspect for new and progressive things, enable advanced and powerful communications for citizens (Atta et al., 2020). RFID can help with the implementation of smart signals. It can be used in the form of a passive tag that is connected to the automobile and can be detected by the RFID reader. The government can help insert the tags in the vehicle plates (Atta et al., 2020). For successful implementations, the issues on invasion of privacy must be addressed first. The stages of advanced traffic management in smart cities are illustrated in Figure 6.

In the future, in approximately 10 years, advanced traffic management may experience steady and accelerating progress. Navigant Research has projected that the "global market for advanced traffic management will be worth more than $1.1 billion in 2019. Annual revenue is expected to grow to nearly $3.8 billion by 2028, representing a compound annual growth rate of 14.2 percent" (Citron, 2019).

Kiger predicted that over the next several decades smart traffic signals will be influential with the increasing use of connected vehicle technology that will enable communication among vehicles and between vehicles and the surrounding infrastructure (Kiger, 2022). In the future, all vehicles and travelers may be connected. Smart signals may work based on the information sent by cars about their locations, directions, and planned route (Kiger, 2022).

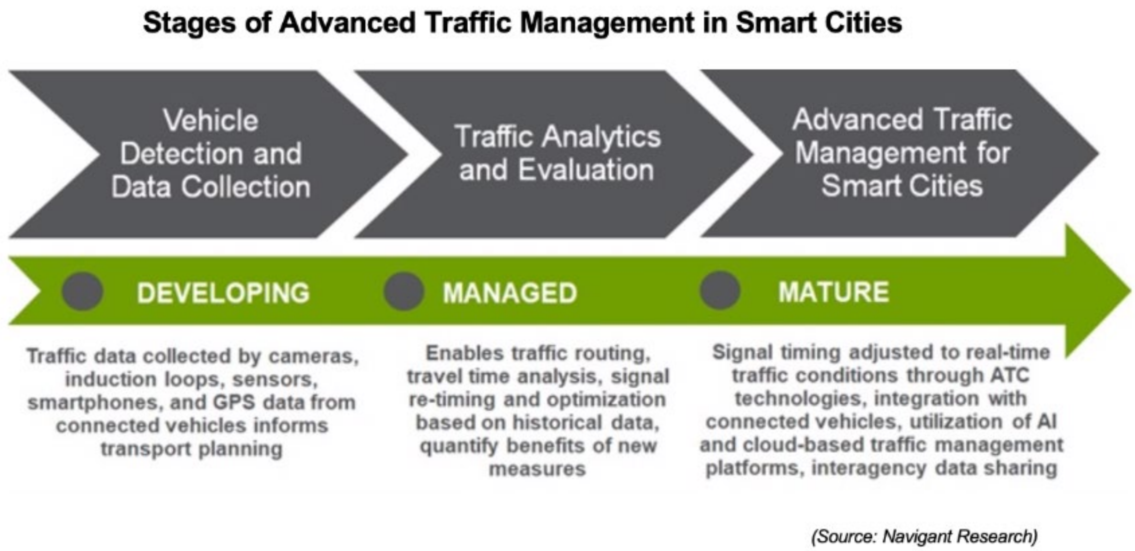


Figure 6. Stages of advanced traffic management in smart cities.

Source: (Citron, 2019)

Benefits, Limitations, and Uncertainties

Smart signals and ATCSs have benefits and limitations. They can make traffic operations efficient and adapt to day-to-day traffic fluctuations (Stevanovic, 2010). The smart signal can decrease congestion on roads controlled by traffic lights (ITS, 2012). Some of the quantitative benefits of ATCS systems include (FDOT, 2016):

- Reduced travel time,
- Fewer stops,
- Reduced fuel consumption/emissions,
- Decreased side street delay,
- Reduced time of saturated conditions, and
- Reduced crashes.

According to (FHWA, 2017), ATCSs can enhance travel time by 10 percent in general and 50 percent after replacing outdated signal timing. A survey asking various agencies about their experience with ATCSs was conducted as part of a 2010 NCHRP study. The survey included over 16 state DOTs, and some international agencies (China, Canada, Australia, etc.). The results of the survey conveyed that over 60 percent of the agencies noted a decrease in travel times with ATCSs, and over 70 percent of the agencies affirmed that ATCS surpass their preceding system (Stevanovic, 2010).

Similarly, the 2010 Atlanta Smart Corridor project assessed the effectiveness of the integration of SCATS (an ATCS system) and Transit Signal Priority (TSP) on an 8.2-mile segment between the City of Marietta and Atlanta, Georgia. The integration reduced travel time by 22 percent and total vehicle delay by 40 percent during all peak periods. The benefit to cost ratio was also projected to be 25:1 (Salem et al., 2015). Another study has also proved that the implementation of ATCS can decrease the number of stops, intersection delays, and queue lengths by 37 percent, 37 percent, and 23 percent, respectively (Stevanovic, 2010).

The performance of ATCS was evaluated on a six-mile segment in the northern metropolitan area of Detroit, Michigan. SCATS, an ATCS system, was compared to a conventional preset timing signal control. The findings indicated that ATCSs can help reduce the number of vehicle stops on the corridor. For that study, the system helped reduce the total crashes per mile per year by 28.84 percent between 1999-2001 and 2003-2008. Permanent injury, temporary injury, and slight bruises-level crash severity were reduced by 49 percent, 51 percent, and 36 percent, respectively, during the same period (Salem et al., 2015).

Other advantages of ATCSs compared to conventional signal systems are that ATCSs can (FHWA, 2017; Salem et al., 2015):

- Continuously distribute green light time equitably for all traffic movements
- Improve travel time reliability by progressively moving vehicles through green lights
- Reduce congestion by creating a smoother flow
- Prolong the effectiveness of traffic signal timing

Despite the many benefits of ATCSs, they have the following limitations (FDOT, 2016):

- The ATCS systems are tools to manage traffic and do not solve all traffic problems.
- ATCS does not add capacity to the roadway nor eliminate oversaturated conditions. Most agencies report that their ASCT systems perform the same or worse than actuated coordinated signal timing when operated in oversaturated conditions.
- ATCS systems require oversight.
- ATCS system infrastructure is complex and has more components than other traffic signal systems with each component playing a critical role in the operation of the system.
- ATCS systems react quickly, but not immediately. ASCT systems require several minutes for a problem to be present (such as high detector occupancy) before the system acts. When the system senses a traffic condition that needs to be mitigated, the system can take several minutes before the 'improved' timing is fully implemented. Further, ASCT systems are typically slow to return to off-peak/normal conditions.

Some of the ATCS users highlighted that the challenges they faced were mostly related to communications, learning how to operate the system, and hardware issues.

Interaction Between Area, Subareas, and Other Areas

Smart and advanced signal timing and optimization systems are related to many of the congestion mitigation areas in this report. The connections exist between smart and advanced signal timing and optimization systems, CAVs, TSM&O, and other smart transportation technologies. For example, connected vehicle (CV) technologies are going to enable the use of smart traffic signals (Kiger, 2022). As highlighted previously, as CV technologies become universal, communication among vehicles and between vehicles and the surrounding infrastructure will become evident (Kiger, 2022). Additionally, the advanced signal timing and optimization systems are included as part of TSM&O strategies. As part of the whole picture, smart navigation is an important piece of smart and advanced signal timing and optimization systems.

Traffic Incident Management (TIM)

This section incorporates a summary of the review on TIM. It entails a description of TIM and its potential in alleviating congestion. Additionally, the summary integrates an exploration of both current and future technologies within the context of TIM.

Definition and Subareas

Definition

TIM refers to a coordinated, multi-agency approach aimed at detecting, responding to, and clearing traffic incidents and restoring traffic capacity as efficiently and safely as possible to minimize their impact on traffic flow (Federal Highway Administration, 2010). The incidents might be a result of crashes, vehicle breakdowns, hazardous material spills, road issues, etc. TIM involves the coordination of various stakeholders, including law enforcement, emergency responders, transportation agencies, towing services, and other appropriate entities.

Subareas

TIM activities are typically categorized into five interrelated functional classes, which can be defined as subareas: (1) detection and verification, (2) coordinated response, (3) scene management, (4) clearance, and (5) traffic management, which includes motorist information. The definitions of the subareas are described below (National Academies of Sciences Engineering and Medicine, 2022):

1. **Detection and verification:** Detection refers to identifying that an incident has occurred. Incidents may be observed by motorists, police patrol, aerial surveillance, roaming service patrol, or through automated systems like cameras. Verification determines the exact location and nature of the incident. Precise information ensures that the most suitable personnel and resources are dispatched to the scene. This verification can occur on-site with response personnel, remotely using closed-circuit television (CCTV) or automated collision notification systems.

2. **Coordinated response** to incidents start with a series of planned strategies to provide optimum deployment of appropriate personnel and equipment and activates suitable communication links and motorist information media as the incident is verified. Timely and effective response reduces the duration of the incident, and therefore, the time of roadway operation at a reduced capacity.

3. **Scene Management** effectively coordinates and manages on-scene resources. Effective scene management increases safety for crash victims, motorists, and responders; coordinates responder activities; and decreases the impacts of an incident on the roadway system.

4. **Clearance** involves the safe and timely removal of any wreckage, debris, or spilled material from the roadway.

5. **Traffic management with motorist Information** applies traffic control measures onsite and in areas affected by an incident. It includes the dissemination of incident-related information to affected motorists using various methods, such as dynamic message signs (DMS), highway advisory radio (HAR), commercial radio, television broadcasts, and telephone information systems.

The timeline of stages in the TIM process is shown in Figure 7.

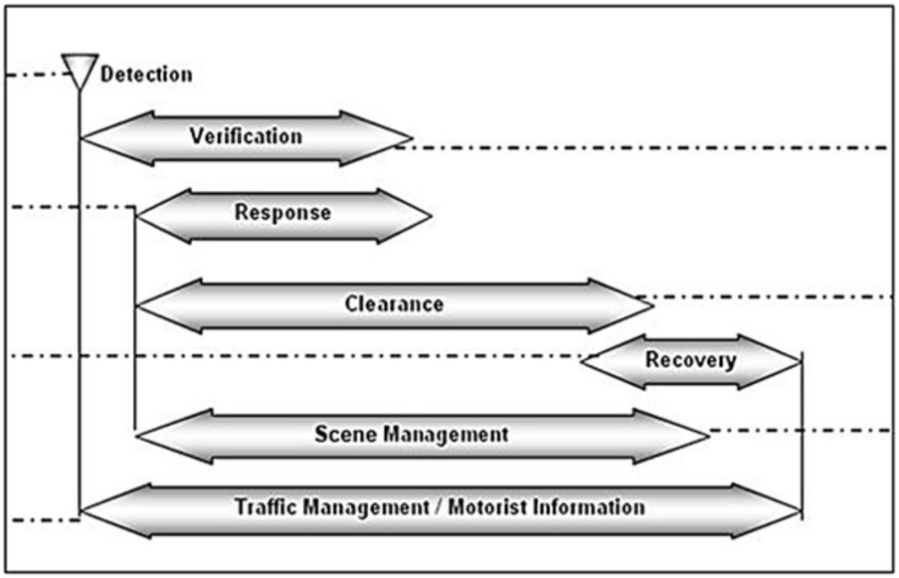


Figure 7. The timeline of stages in the TIM process.

Source: (FHA, 2010)

Congestion Reduction Strategies, Conditions, and Approaches

TIM aims to reduce the duration and severity of traffic disruptions caused by accidents, breakdowns, or other incidents and, therefore, can alleviate traffic congestion by quickly detecting incidents, coordinating efficient responses, managing scenes effectively, and promptly clearing roadways. The shorter the roadway clearance time, the less the traffic is affected (National Academies of Sciences Engineering and Medicine, 2022). The role of TIM is to manage non-recurring congestion by efficiently managing incidents that disrupt the traffic flow. This can be accomplished by reducing the time the lanes are blocked, efficient traffic control, quick clearance, minimizing secondary accidents, and timely dissemination of real-time information to motorists. TIM is adaptable and beneficial across various roadway types, including highways, freeways, urban roads, and arterial roads, where incidents like crashes, breakdowns, construction activities, and signal malfunctions frequently happen.

Success relies on well-trained responders, effective communication, and interagency coordination. Approaches include established incident management protocols, real-time technology integration, and roadside assistance deployment. Education on safe driving practices and yielding to emergency vehicles is vital. Collaborating with local authorities to streamline emergency response enhances congestion alleviation efforts, ensuring smoother traffic flow and minimizing incident-related disruptions.

Current and Future Technologies

TIM employs several technologies to detect, respond to, and manage incidents on roadways. Some of these technologies include:

Traffic Cameras: High-resolution cameras placed strategically along roadways provide real-time visual information, aiding in incident detection and assessment. Transportation departments and law enforcement agencies are deploying cameras at critical roadway locations. These are monitored from centralized control rooms, allowing traffic operations centers to identify incidents when they happen. First responders can be alerted immediately and dispatched to the correct location without someone having to call. Cameras also allow for active management of traffic signals since controllers can watch lines form and adjust signal timing accordingly (Robare, 2023).

Roadside Sensors: Sensors and detectors installed on roads monitor traffic flow, detecting anomalies like congestion or sudden slowdowns, which can signal potential incidents.

ITS: ITS technologies include dynamic message signs, traffic signal coordination systems, and vehicle-to-infrastructure (V2I) communication to manage traffic flow and provide information to motorists.

Incident Management Software: Specialized software assists in incident documentation, resource allocation, and coordination among responding agencies for efficient incident response.

Global Positioning System (GPS) and Geographic Information Systems (GIS): GIS tools integrated with GPS data aid in mapping incident locations, planning alternate routes, and providing navigation guidance to motorists.

Communication Systems: Advanced communication networks, including radio and mobile apps, facilitate real-time communication among response teams, enabling swift coordination during incidents.

Automatic Vehicle Location (AVL) Systems: AVL systems track and locate emergency response vehicles, helping optimize deployment and route planning.

Remote Traffic Monitoring: Remote monitoring technologies enable traffic management centers to oversee traffic conditions and incidents in real time, allowing for timely responses.

In the next five years, innovations in existing technologies can be expected, as well as the use of machine learning (ML), AI, and CAV technologies. ML algorithms are used to enhance incident forecast, detection, and classification. CAVs can communicate with each other and with traffic management systems, providing real-time information about their status and surroundings. This connectivity can enhance incident detection, response coordination, and overall traffic flow management. Additionally, data analytics and predictive modeling will be more critical for transportation planners. In the next two decades and beyond, augmented reality (AR) and virtual reality (VR) technologies can enhance incident response by providing responders with immersive and augmented views of incident scenes (Zhu & Li, 2021).

Benefits, Limitations, and Uncertainties

Benefits

TIM provides numerous advantages in alleviating congestion:

- Quick incident detection and response minimize vehicles' duration in congested or slowed traffic and enhance road safety by mitigating the risk of secondary accidents.
- Traffic management measures employed during incidents, such as rerouting, lane management, or signal coordination, maintain a smoother traffic flow and decrease congestion buildup.
- Major benefits of TIM include swift incident clearance, preventing secondary delays, improving traffic flow, safety, environmental impact, and overall efficiency.
- Disseminating real-time information to motorists about incidents and alternative routes empowers them to make informed decisions, thereby reducing the impact of congestion (National Academies of Sciences Engineering and Medicine, 2022).

Limitations

Several challenges and issues can arise in TIM, which might delay congestion reduction:

- Public safety agencies are typically the first to be notified of incidents, but notification of support responders, especially transportation agencies, may be inconsistent.
- The absence of formal guidelines for notifying support responders, or the inconsistent adherence to established guidelines, can result in varying notification practices.
- After major incidents, dispatchers may receive multiple calls from motorists reporting the same incident. This overload can limit their ability to address other emergencies promptly.
- In areas with lower traffic volumes, incidents may go undetected for longer periods (Federal Highway Administration, 2010).

Uncertainties

Certain decisions during TIM procedures, such as lane closures, could worsen congestion. These choices, impacting quick clearance goals, should involve consultation among all responding disciplines. Each scenario warrants tailored evaluation. In some instances, placing equipment across a lane might protect responders but could block multiple lanes, increasing the risk of additional collisions. Conversely, road closures can hinder responders from bringing equipment to the scene (National Traffic Managenent Coalition, 2006).

Interaction Between Area, Subareas, and Other Areas

The subareas in TIM are highly related, and TIM closely interacts with Smart and Advanced Signal Timing and Optimization Systems, Smart Navigation Systems, and TSM&O.

Transportation Systems Management and Operations (TSM&O) Strategies

This section provides a summary of the literature regarding TSM&O strategies, describes TSM&O strategies, and discusses how they can effectively alleviate traffic congestion.

Definition and Subareas

Definition

The Federal Highway Administration (FHWA) defines TSM&O as “the use of strategies, technologies, mobility services, and programs to optimize the safety, mobility, and reliability of the existing and planned transportation system” (FHWA, 2018). The Moving Ahead for Progress in the 21st Century Act (MAP-21) noted that TSM&O involves employing “integrated strategies to optimize the performance of existing infrastructure through the implementation of multimodal and intermodal, cross-jurisdictional systems, services, and projects designed to preserve capacity and improve security, safety, and reliability of the transportation system (23 U.S.C. 101(a)(30))” (ARC, 2020). TSM&O can also be defined as the optimization of the performance of multimodal and intermodal transportation systems and infrastructure using planning processes, programs, services, and projects for enhanced capacity, safety, security, and reliability (ARC, 2020; DVRPC; FDOT, 2022b; FHWA, 2020b; MnDOT, 2019a; MoDOT, 2017). Thus, it is about actively managing the transportation network to improve safety and mobility (ARC, 2020). The description of TSM&O components is shown in Figure 8.

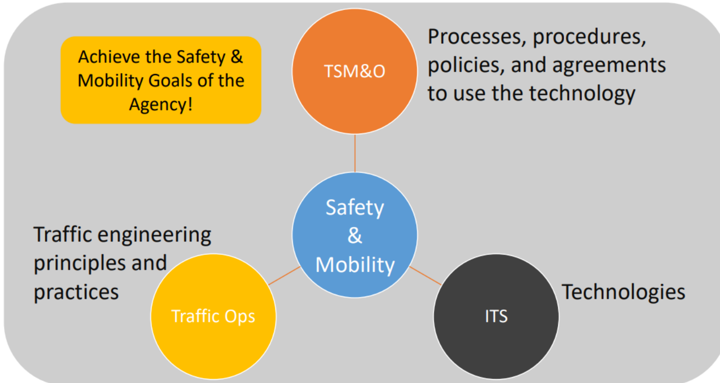


Figure 8. Description of TSM&O.

Source: (Alluri, 2021)

From all the definitions, it can be affirmed that the three main goals of TSM&O are preserving capacity, improving safety, and reliability of the transportation system.

Subareas

TSM&O can be subdivided into a wide range of strategies. Some of the strategies include (ARC, 2020; FDOT, 2022b; FHWA, 2020b; MnDOT, 2019a):

- ITS strategies (e.g., dynamic message signs, traveler information)
- Arterial management (e.g., adaptive signal control technologies and traffic signal maintenance)
- Managed lanes (e.g., express lanes and tolls)
- Traffic incident management
- Work zone management
- Traffic signal timing coordination and control
- Ramp metering and management
- Road weather management
- Special event management
- Transit management
- Freight management
- Harmonization of traffic flow
- Active traffic management
- Integrated corridor management
- Variable speed limits
- Congestion pricing
- Active transportation and demand management
- Access management
- Connected and automated vehicles

Congestion Reduction Strategies, Conditions, and Approaches

The Missouri Department of Transportation (MoDOT) underlined that TSM&O strategies can help directly address many of the root causes of recurring and non-recurring congestion (MoDOT, 2017). However, knowledge, skills, and techniques are needed to employ the comprehensive TSM&O solutions quickly and at low cost. TSM&O allows agencies to use technology and collaboration to yield flexible solutions, which require less funding and benefit more areas and travelers (ARC, 2020). For example, crashes, roadway incidents, weather conditions, work zones, or special events are the source of about half of the congestion and delays; proper TSM&O strategies can be used to address the issues. Roadway construction or capacity expansion solutions are determined to be ineffective in reducing congestion. Despite this, the construction solution requires considerable time and money. On the other hand, TSM&O strategies such as traffic incident management, road weather management, and work zone management have proved to be successful and cost-effective in addressing congestion (ARC, 2020).

TSM&O technologies and context-sensitive approaches are used to optimize safety and to accomplish the goal of zero fatalities. This requires incorporating the needs of all travelers, including those in vehicles or transit, riding their bicycles, or walking. TSM&O can forge reliable travel times when planned and unplanned interruptions are managed to decrease system delays. It can help with travel time predictability and lessen interruptions due to non-recurring congestion sources (ARC, 2020).

In its 2017 TSM&O Implementation guidebook, the Pennsylvania Department of Transportation (PennDOT) correlated TSM&O solutions to congestion causes, detailed in Table 1. Strategies like integrated corridor management and traffic center operations address both recurring and non-recurring issues, while traveler information primarily tackles non-recurring congestion sources.

The three main ways TSM&O can help reduce congestion include minimizing the traffic impact of unplanned events, mitigating recurring congestion, and maintaining mobility during planned events (Figure 9).

Table 1. TSM&O Solution Matrix

TSMO Solutions	Causes of Congestion					
	Bottlenecks	Traffic Incidents	Inclement Weather	Work Zones	Poor Signal Timing	Special Events
Integrated Corridor Management	x	x	x	x	x	x
Hard Shoulder Running	x	x				x
Managed Lanes	x	x	x			x
TIM Teams		x				
Freeway Service Patrols		x		x		x
Smart Work Zones				x		
Traffic Signal Enhancements					x	
Transit Signal Priority					x	
Traveler Information		x	x	x		x
Ramp Metering	x	x				x
Bridge De-icing			x			
Commercial Vehicle Operations						
Dynamic Lane Assignment	x	x		x		x
Junction Control	x	x		x		x
Queue Warning	x	x		x		x
Variable Speed Displays		x	x	x		
Dynamic Rerouting		x		x		x
RWIS			x			
Dynamic Curve Warning						
Traffic Management Center Operations	x	x	x	x	x	x
Traffic Incident Detection		x				
DMS		x		x		x
CCTV	x	x	x	x		x

Source: (PennDOT, 2017)

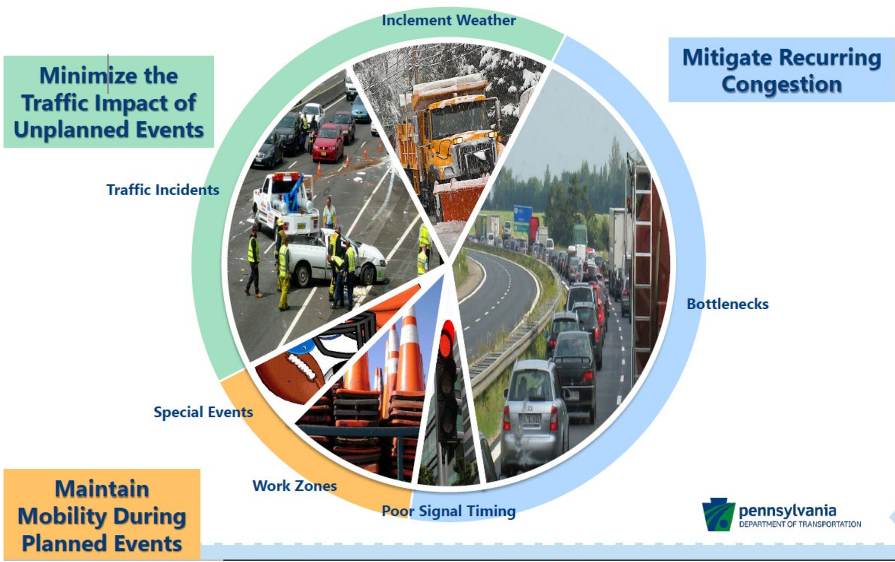


Figure 9. TSM&O congestion reduction strategies.

Source: (PennDOT, 2017)

Some of the necessary aspects to consider when implementing TSM&O include (ARC, 2020):

Technology Considerations

When new technology is used for TSM&O strategies, it may require integration and connectivity with the preceding systems. This may also require coordination at different levels across various departments. Technical experience and knowledge of the systems engineering process are important for TSM&O projects.

Stakeholder Coordination

Stakeholder coordination is important in the success of TSM&O strategies. All interested parties, including maintenance and IT people should meet early in the process to discuss the requirements of the systems. Proper stakeholder coordination will enable TSM&O to be designed and implemented successfully.

Communication Network

Communication networks are becoming more and more important in transportation and for TSM&O. Communication between stakeholders about responsibilities and experience can be crucial for the success of a TSM&O project. The agency deploying TSM&O should think through at least the following: bandwidth and latency requirements, uptime requirements, network access, technology hardware and network security, necessary system upgrades, and regular system maintenance requirements.

Data Considerations

Many TSM&O strategies use various datasets. Important steps in data planning, operation, and maintenance for TSM&O include data access, collection, cleaning, validation, management, integration, processing, and storage. As technologies change and innovation continues, regional data sharing and governance will be important for the future of TSMO systems. Considering big and real-time data enabled by connected vehicles and internet of Things (IoT) sensors are becoming increasingly important and accessible. The Atlanta Regional Commission (ARC) stated that "regardless of how advanced an agency may be, every organization will likely experience challenges when implementing TSM&O strategies. This is in part because TSM&O systems are multi-agency and multimodal in nature, requiring organizations to think outside their own structure for data sources and end-users. In addition, data should conform to a minimum quality, standardized formats, and regional terminology and meaning" (ARC, 2020).

Current and Future Technologies

Many technologies are used in TSM&O. For example, radar and vision sensors, communication technologies such as wireless, and the Internet of Everything (IoE) are applicable in TSM&O. In the long-term future, most of those technologies will evolve and become ubiquitous.

Benefits, Limitations, and Uncertainties

Benefits

TSM&O strategies have many benefits and can help reduce traffic congestion in many ways. Some facts surrounding the benefits of TSM&O strategies are explained as follows (Alluri, 2021):

- TSM&O strategies are proven to improve safety and mobility of the transportation network.
- The safety and operational benefits are unique to the strategy.

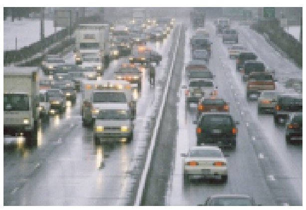
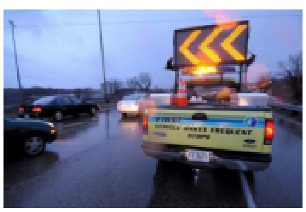
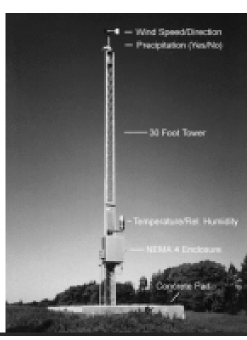
- While some strategies provide direct quantifiable benefits, it is difficult to measure the impacts of some strategies.
- TSM&O strategies provide feasible alternatives to achieve the safety and mobility goals of the agencies.

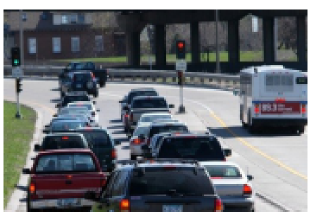
TSM&O strategies are more cost-effective and can be implemented more quickly than capacity adding projects (MoDOT, 2017). The Michigan Department of Transportation (MDOT) labels their TSM&O program as a low-cost, high-impact solution for safer roads, less congestion, and greater reliability (MDOT). TSM&O can help address the root causes of congestion by improving the performance of transportation systems, resulting in the following specific outcomes (ALDOT, 2023; ARC, 2020; MDOT; MoDOT, 2017):

- Efficient trips and commutes
- Smoother and more reliable traffic flow
- Safer roadways, with fewer crashes, injuries, and deaths
- Better, easier-to-use traveler information and road weather management
- Fewer wasted gallons of gas, enhancing livability and sustainability
- Better, faster, cheaper, safer, and smarter results
- A more efficient use of resources

Several TSM&O strategies along with their approaches and benefits are described in Table 2.

Table 2. Benefits of Example TSM&O Strategies

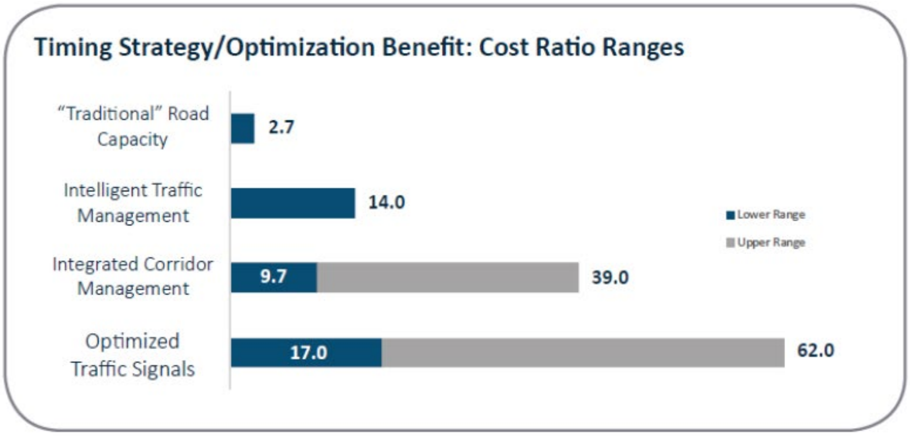
TSMO Strategy	How It Works[1]	Observed Benefits
Traveler Information 	Provides current and anticipated travel and weather conditions, route, and mode options (and other information) via dynamic message signs, 511, web, social media, and text. Supports travelers' optimal choice of trip route, timing, and mode	**National[2]** 511 customer satisfaction of 68–92% Route-specific travel times: 5–13% increase in on-time performance (i.e., reliability)
Traffic Incident Management 	Applies incident detection, verification, response, clearance, crash investigation, medical response, and traffic control Organizes the management and clearance of disruptions and responses to emergencies and ensure incident site safety and restoration of traffic flow	**National[2]** Reduced duration of traffic incidents 30-50% resulting in • Reduced congestion • Improved reliability • Improved safety including reduction in secondary crashes
Safety Service Patrol 	Locates, assists, and removes disabled vehicles, crashes, and debris from freeways; assists State Patrol with crash site traffic control and first aid Reduces congestion, improves safety, and provides a customer-oriented approach to freeway operations	**National[2]** B/C ratio = 5:1 to 25:1 **MnDOT** MnDOT Freeway Incident Response Safety Team or FIRST: B/C ratio = 15:1
Road Weather Management Systems 	Generates advance and current information regarding disruptive weather conditions by combining roadway environmental sensing, weather information, treatment and clearance strategies and weather information dissemination Improves agency capacity to minimize traveler delay and improve agency efficiency of weather-related roadway maintenance	**National[2]** Wet pavement detection and advisory system reduced crashes by 39% B/C ratio = 2:1 to 10:1

TSMO Strategy	How It Works[1]	Observed Benefits
Work Zone Management Systems 	Provides dynamic, traffic-responsive traffic control (lane use, speeds, warnings) in construction work zones Improves safety to drivers and construction workers and improves traffic flow	**National[2]** B/C ratio = 2:1 to 42:1
Traffic Signal Optimization 	Provides traffic-responsive or traffic adaptive signal operations at intersections for corridor and network optimization and event responsiveness Minimizes delay throughout corridor and network	**National[2]** Reduced traffic delay 15–40% Reduced travel time up to 25% B/C ratios sometimes exceeding 50:1
Adaptive Ramp Metering 	Controls traffic flow (rate and spacing) entering freeway based on actual traffic conditions Minimizes main line traffic disruptions and safety hazards and improves travel time	**National[2]** • Increased freeway throughput 13–26% • Decreased crashes 15–43% **MnDOT** • Increased throughput 14% • Decreased crashes 25% B/C ratio = 15:1

1. AASHTO TSMO Guidance
2. FHWA

Source: (MnDOT, 2019b)

TSM&O can improve traffic by "expediting traffic incident clearance, optimizing traffic signal timing in real time, providing alerts to travelers, disbursing platoons as they enter a freeway, and prompting the prewetting of a roadway to prevent ice from forming in the first place" (MoDOT, 2017). The benefit-to-cost ratios of various signal timing strategies, compared to traditional road expansion, are presented in Figure 10.



SOURCE: Intelligent transportation systems. Capitol Research. Council of State Governments, April 2010: Transport for London, 2007; Intelligent transportation system benefits, costs, deployment, and lessons learned desk reference: 2011 update, US Department of Transportation, September 2011; Urban mobility plan, Seattle Department of Transportation, January 2008; McKinsey Global Institute analysis

Figure 10. Example of a TSM&O benefit: cost ratio ranges.

Source: (ARC, 2020)

The Federal Highway Administration (FHWA, 2022) demonstrated how different state departments of transportation (DOTs) are using TSM&O strategies to enhance safety, reduce delays caused by congestion, save taxpayer dollars, or reduce emissions and their impact on the environment. The summaries include the following state DOTs:

<u>ARIZONA: Innovative Striping and Signage</u>

In the Phoenix metro area, Arizona DOT implemented a sign redesign for drivers to see clearly and lane restriping to improve safety and system performance on a two-mile segment where westbound US-60 merges with I-10. The segment had the highest number of serious and fatal crashes on the Arizona DOT (ADOT) system. A year after completion, ADOT noticed 385 fewer crashes of all severities than in the previous year. For all crash severities for the two-mile segment, a benefit-cost ratio of 1,969:1 (66% percent reduction in crashes) was seen in a year after completion.

<u>FLORIDA: Integrated Corridor Management</u>

FDOT implemented Integrated Corridor Management (ICM) in Orlando, the second-fastest growing city in the United States. The goal of the ICM was to enhance travel time and reliability for residents and visitors while also using incident management on freeways and arterials. The ICM, which involved transit signal priority and adaptive signal control, helped reduce delays by up to 40 percent and enhance bus times.

<u>NEVADA: Traffic Incident Management</u>

Nevada DOT collaborated with other agencies in the state to create a real-time incident-sharing data platform, which uses in-vehicle data and AI to manage traffic and prevent crashes. The platform enables efficient incident management through real-time sharing of incident information across agencies, first responders, and the public. It was effective at reducing incident response times by 12 minutes and decreasing secondary crashes in Southern Nevada. It also helped inform drivers in real time when an incident happened.

<u>MARYLAND: Traffic and Event Management</u>

Maryland DOT established the Coordinated Highways Action Response Team (CHART), which is a statewide comprehensive and advanced traffic management system. CHART uses many TSM&O strategies, including traffic management, incident management, and traveler information. It helps a motorist every 16 minutes on average and manages traffic at a crash/incident location every 22 minutes. As a result, it eliminates about 225-250 secondary crashes a year. CHART also helped drivers save about $1.5 billion in fuel and delay costs yearly.

MICHIGAN: Improved System Reliability

Michigan DOT (MDOT) used Active Transportation Management (ATM) strategies to dynamically manage congestion, operations, and incident management on US-23 through Washtenaw and Livingston Counties. The employed strategies included dynamic lane control and shoulder use, variable speed advisories, and queue warnings. The solutions enabled improved safety, made travel times more reliable by up to 56 percent, enhanced corridor speed by up to 19 miles per hour, and reduced congestion.

Limitations and Uncertainties

TSM&O relies on accurate, real-time data to manage transportation systems effectively. In some areas, limited or unreliable data from sensors, cameras, and GPS can hinder decision-making. Inconsistent or outdated data from sources like traffic sensors, mobile apps, and social media further complicates traffic management. Successful TSM&O requires coordination across multiple stakeholders—governments, law enforcement, transportation agencies, private sector, and the public. Lack of coordination or differing priorities can cause delays and inefficiencies, while varying technical expertise and resources can lead to uneven implementation.

Interaction Between Area, Subareas, and Other Areas

TSM&O strategies interact with most of the other areas considered in this report. Most of the congestion areas considered in this report are the strategies under the TSM&O umbrella, including CAVs, Smart and Advanced Signal Timing and Optimization Systems, Incident Management, Congestion and Road Pricing, and other areas using technologies.

Multimodal Transportation

In this section, a summary of the literature review on multimodal transportation is presented. It includes different transportation modes, their effects on congestion reduction, conditions, and approaches, benefits, limitations, and uncertainties.

Definition and Subareas

Definition

Multimodal transportation refers to the use of multiple modes of transportation, such as cars, buses, trains, bicycles, and walking, within a single journey or transportation system. It involves seamlessly integrating different modes of transport to provide passengers with convenient and efficient travel options (Chen Peng, Boyd Tia, & Williams Kristine, 2022). Multimodal transportation systems are designed to offer travelers flexibility, accessibility, and connectivity, allowing them to choose the most suitable mode of transportation based on factors such as distance, cost, time, and personal preferences. Figure 11 presents connected, door-to-door journeys.

Subareas

Multimodal transportation encompasses all modes of travel utilized by individuals including:

- **Public Transit**: Commuter trains, buses, subways, ferries, trams that operate on fixed routes and schedules within urban and suburban areas.
- **Active Transportation:** Walking and biking. These modes are often used for short-distance trips and can complement other forms of transportation.
- **Micro-Mobility Modes:** This includes modes such as e-bikes and scooters.
- **Freight:** This is the movement of goods, where shipments may utilize a combination of trucks, trains, ships, and airplanes to reach their destination efficiently
- **Private Cars**

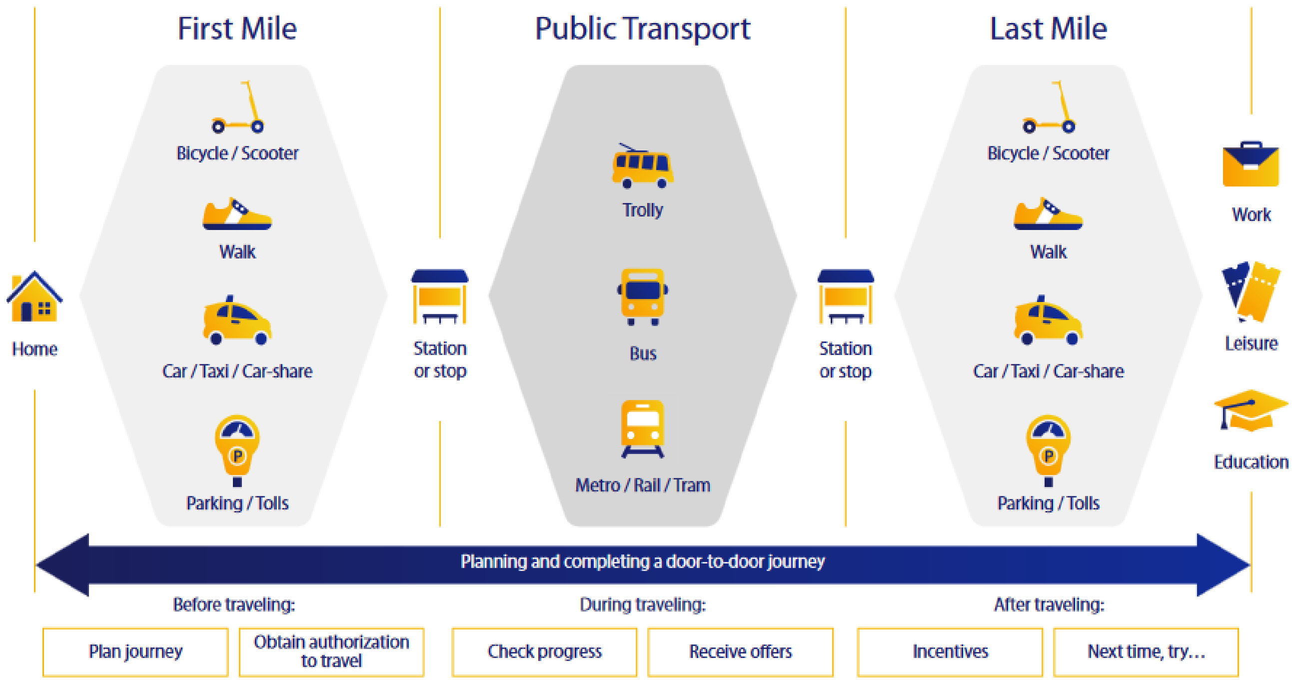


Figure 11. Connected, door-to-door journeys.
Source: (VISA, 2020)

Congestion Reduction Strategies, Conditions, and Approaches

A multimodal transportation system can alleviate traffic congestion by reducing the number of automobiles on the roads. It requires the entire mobility infrastructure to be designed in a variety of ways for people to get around, along with easy commuter access to public transit and ease of transition between modes (STREETLIGHT DATA, 2023). Multimodal transportation can help relieve recurring congestion by offering alternative transportation options to single-occupancy vehicles by providing efficient public transit services, bike lanes, pedestrian pathways, and other active transportation infrastructure. Multimodal transportation encourages people to choose alternative modes of travel. Non-recurring congestion can be alleviated by using real-time information and smart technologies that can enable multimodal users to adjust their plans dynamically in response to incidents.

Urban and arterial roads can benefit from well-designed multimodal transportation. In densely populated urban areas, by encouraging modal shifts from cars to public transit, walking, and cycling, multimodal transportation can considerably alleviate traffic congestion in city centers and surrounding neighborhoods. On arterial roads, by connecting different parts of a city or region, multimodal transportation strategies, such as dedicated bus lanes, bus rapid transit (BRT) systems, and integrated transport hubs, can improve the flow of traffic by prioritizing high-capacity public transit and reducing reliance on single-occupancy vehicles.

Current and Future Technologies

The leading technologies used in multimodal transportation include (Intellias, 2024):

- Intelligent transportation systems: used to plan, manage, and optimize transportation across different modalities,
- Traveler services information and payments,
- Connected infrastructure,
- Big data analytics, and
- Mobility as a service (MaaS), which offers travelers a roster of transportation options supplied by public and private agencies.

Benefits, Limitations, and Uncertainties

Benefits

A multimodal transportation system offers a comprehensive approach to address traffic congestion through the integration of different modes of transportation while placing public transportation as the backbone of the regional transportation system. By embracing multimodal transportation strategies, cities and regions can make significant progress in addressing congestion while also improving overall mobility and promoting sustainable transportation options. Strategies that promote cycling to transit have the potential to immediately increase transit ridership, while strategies for creating seamless transit systems can set up transit for long-term success. Park-and-ride systems may also be useful in certain suburban and exurban contexts as well.

Limitations

Multimodal transportation faces some challenges, particularly with last-mile connectivity. Poor infrastructure for walking, cycling, and micro-mobility, coupled with limited access to public transit stations, often drives travelers to use personal vehicles for short trips. Additionally, the reliability and frequency of services such as buses, trains, and shared mobility are crucial; delays and disruptions can deter users. Coordination, integration, and infrastructure investment are also critical concerns that need addressing.

Uncertainties

Inconsistent regulations and complex permitting processes hinder multimodal transport development. Streamlining regulations, fostering public-private partnerships, and ensuring policy coherence are essential. Additionally, behavioral and cultural factors pose challenges. Shifting from private vehicles to public transit and active transport requires altering traveler behavior and overcoming car-centric urban planning and cultural preferences for car ownership.

Interaction Between Area, Subareas, and Other Areas

Multimodal transportation intersects closely with public transportation systems, incorporating buses, trains, light rail, and ferries for success. Additionally, integrating TSM&O strategies enhances its effectiveness. By harmonizing various transportation modes like public transit, walking, cycling, and ride-sharing with the implementation of TSM&O strategies, multimodal transportation fosters an integrated and efficient system. Smart signal timing systems can further optimize traffic flow, bolster safety, and elevate mobility, reducing traffic congestion.

Shared Transport Systems

This section summarizes the literature review on shared transport systems. It describes shared transport systems, accentuating their potential to mitigate congestion. Additionally, the summary integrates an exploration of both current and future technologies within the realm of shared transport systems.

Definition and Subareas

Definition

Shared transport systems, also known as shared mobility, is a mode of transportation where individuals share the use of a vehicle, bicycle, or other modes. This innovative transportation strategy allows users to access transportation modes on a short-term and on-demand basis (Shaheen, Cohen, Chan, & Bansal, 2020).

Subareas

The key areas of shared mobility are presented in Figure 12. Shared transport systems can be subdivided into the following categories:

- **Sharing a vehicle or device** includes services that enable vehicle sharing, such as **car sharing, scooter sharing, and bike sharing.**
- **Sharing of passenger ride services** that enable (1) ridesharing (**carpooling or vanpooling**), (2) on-demand ride services (**transportation network companies, ride splitting, e-hail)**, and (3) micro transit (fixed routes and fixed scheduling, and flexible routes and flexible scheduling).
- **Sharing a delivery ride** includes courier network services, including person-to-person **(P2P**) delivery services and paired on-demand passenger ride and courier services.

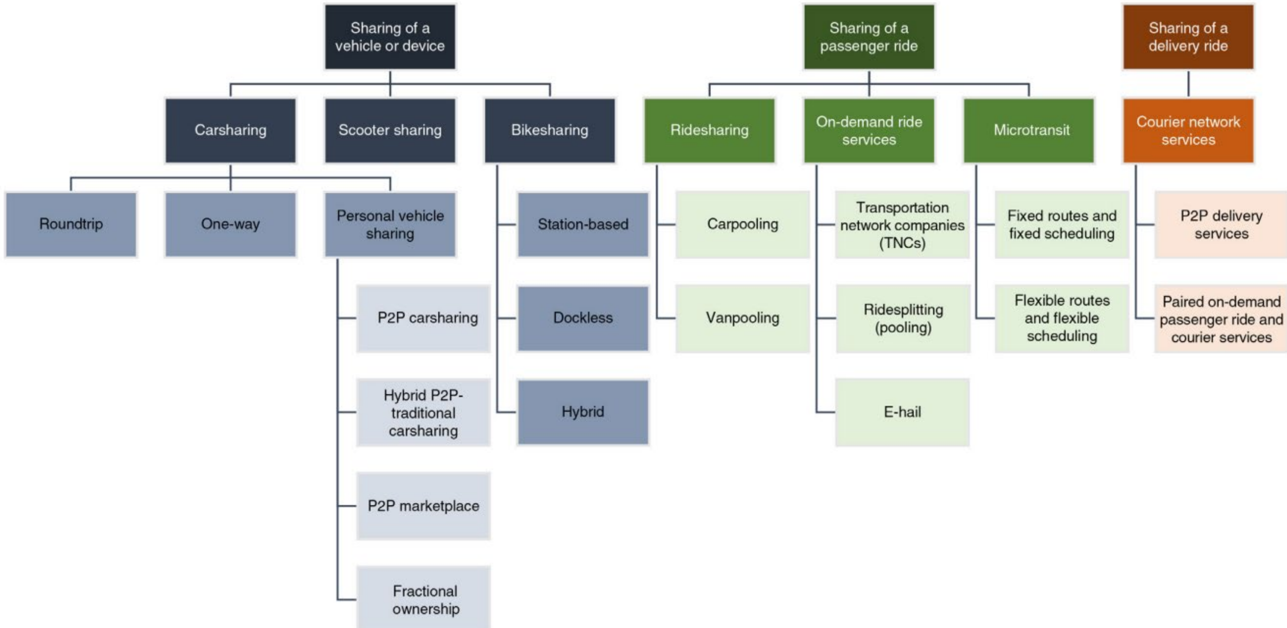


Figure 12. Key areas of shared mobility.

Source: (Shaheen et al., 2020)

Congestion Reduction Strategies, Conditions, and Approaches

To reduce congestion using shared transport systems, cities can expand the availability of shared mobility options like bikes, e-scooters, and car-sharing services, integrating them seamlessly with public transit to facilitate easy transfers. Incentivizing the use of these services through subsidies, discounts, and priority lanes can make them more attractive to users. Additionally, awareness campaigns and partnerships with workplaces and schools can promote behavioral shifts away from private car use.

Success hinges on robust infrastructure, such as dedicated lanes and convenient parking for shared vehicles, alongside supportive policies that encourage shared mobility and discourage private car use. Public-private partnerships can enhance service quality and coverage while addressing safety and security concerns to build user trust.

Developing integrated mobility platforms and implementing dynamic pricing models can further optimize the use of shared transport services. Starting with pilot programs allows for testing and refinement before scaling citywide, ensuring effective implementation and adoption, ultimately leading to significant congestion reduction.

Micromobility, a new mode of transportation including e-scooters, e-bikes, and bicycles, has gained popularity for short-distance travel at speeds below 15.5 mph. It is used for commuting, recreation, and connecting first and last miles. Effective congestion reduction requires adequate infrastructure, favorable climate conditions, wide service coverage, and equity considerations. Enhancing micromobility also involves improving public transportation to provide integrated and efficient service.

Common shared transport systems include:

Carpooling is a user-run, informal form of ridesharing, which is formed with three or more commuters per vehicle. It provides participants with time and cost benefits through access to a high-occupancy vehicle (HOV) lane and often-tolling discounts. Carpooling can help reduce vehicle miles traveled (VMT) and therefore potentially influence congestion.

Bike sharing programs allow members to check out e-bikes and bicycles from stations located in public spaces and return them to other stations when their rides are complete. Modern systems generally require members to purchase a membership for a specified time (e.g., a daily or annual membership). Members use a key to unlock bicycles at any station, and they can return them to an empty dock at a station near their end destination. Rides that last less than a given amount of time (typically 30 min) are free, while average fees are incurred for longer trips (Hamilton & Wichman, 2018).

Scooter sharing plays a significant role in the contemporary micromobility sector within the transportation world. These compact vehicles, propelled by small electric motors, encompass a variety of forms, including hoverboards, scooters, and skateboards, featuring between one and four wheels. The rising popularity of electric scooters in recent years underscores the growing recognition of micromobility as a viable solution to address urban mobility challenges, particularly those related to traffic congestion.

Numerous studies have explored the viability of shared e-scooters as a mode of public transportation. Positioned within the broader concept of micromobility, shared e-scooters share similarities with bike-sharing, particularly in their likelihood to replace walking trips over other modes of transportation. This alignment underscores their potential as substitutes for short-distance pedestrian journeys, emphasizing the role of shared e-scooters in enhancing and transforming urban micromobility solutions.

(Jiao & Bai, 2020) indicated that e-scooter traveling is a means of transportation between walking and bicycling. It fills the travel demand gap when a trip is too long to walk but too short to ride a bicycle. In another study, Wang et al. (2022) gathered data on what travel modes shared e-scooters can displace, and they found that based on the existing behavioral surveys that public transit trips are not likely to be replaced by shared e-scooter rides. American cities such as Los Angeles, Santa Monica, and Portland reported that trips made using dockless shared electric scooters were previously made using private cars or ride-hailing services such as Uber and Lyft (Monica, 2019). Overall, carpooling, bike sharing, and scooter sharing can improve the utilization of vehicle resources and decrease traffic congestion (Si, Duan, Cheng, & Zhang, 2022; Standing, Standing, & Biermann, 2019).

Current and Future Technologies

Shared transport systems use several technologies, including:

- **Mobile Apps**: These enable users to use the services and to locate vehicles, book rides, make payments, and track their journey in real-time.
- **GPS and Navigation Systems**: This technology is used to track the location of vehicles and to give directions. It can give information about alternative routes and arrival times.
- **Vehicle Telematics**: It can provide information about location, speed, fuel consumption, and engine health that is useful to manage fleet, schedule maintenance, and improve vehicle utilization.
- **Internet of Things (IoT) Sensors**: They can help provide real-time traffic data, parking availability, and vehicle occupancy.
- **Payment Systems**: Electronic payment systems can help with various transactions.

- **Cloud Computing**: It allows the management of large volumes of data and the handling of user demands. It can also be used to analyze user behavior and understand vehicle use. This information can help with the scalability and reliability of the systems.
- **AI and ML**: They can be used to predict demand patterns, optimize routing, and dynamically adjust pricing.
- **Vehicle Sharing Technologies**: These technologies, such as RFID, QR codes, or Bluetooth, enable users to access shared vehicles securely without physical keys. They also verify and confirm user identities to avoid unauthorized use.

These technologies together assist in making shared transport systems convenient, sustainable, and cost-effective mobility options for residents and visitors.

Benefits, Limitations, and Uncertainties

Benefits

Carpooling offers numerous benefits, including reducing traffic congestion by decreasing the number of vehicles on the road, which in turn lowers commuting times and stress. It also cuts transportation costs for participants by sharing fuel and parking expenses. Environmentally, carpooling significantly reduces emissions and fuel consumption, contributing to cleaner air and lower carbon footprints. Additionally, carpooling fosters social interaction and community building as individuals share rides and network during their commutes. Overall, carpooling enhances transportation efficiency and sustainability, making it a practical and eco-friendly option for daily travel.

Micromobility can alleviate urban congestion by offering efficient alternatives to car travel for short distances. It reduces emissions, promotes cleaner air, and lowers carbon footprints. Cost-effective for users and cities, micromobility decreases fuel, parking, and infrastructure expenses. Additionally, it enhances accessibility and connectivity to public transit, encourages physical activity, and provides flexible, convenient transportation options, fostering integrated and sustainable urban mobility.

Findings from a Washington-based study conducted by Hamilton and Wichman (2017) indicated that at the neighborhood level bike-sharing systems seemed to lead to a 4 percent reduction in traffic congestion. In another case study conducted by Fan and Zheng in Beijing, China, they discovered that subway lines experiencing higher bike-sharing intensity exhibited an 8 percent greater growth rate in subway ridership compared to those with lower intensity. Additionally, their predictions indicated a potential 4 percent reduction in traffic congestion during peak hours around subway stations that incorporated bike-sharing trips (Y. Fan & Zheng, 2020).

Fan and Harper identified that around 48 percent of peak hour trips in Seattle fall within the short trip category (0-3 miles), and approximately 18 percent of these journeys have the potential to be replaced by micromobility modes (Z. Fan & Harper, 2022). The study also revealed a decrease of approximately 10 percent in severely congested road segments and an increase of one percent in non-congested road segments. The results further indicate that the substitution of micromobility modes has a more pronounced positive impact on urban arterials compared to freeways or expressways. This is because short car trips predominantly occur on urban arterials rather than on freeways and highways (Z. Fan & Harper, 2022).

Limitations

Shared transportation systems also have some limitations. Shared transportation systems face challenges such as limited coverage and availability, variable service quality, dependency on personal vehicles, difficulty integrating with existing infrastructure, and potential resistance from users accustomed to individualized transport. It was found that in a medium-scale setting where the network size or demand is constrained, ridesharing or carpooling does not significantly contribute to alleviating traffic conditions, thereby limiting the potential for substantial trip reduction through sharing (Alisoltani, Leclercq, & Zargayouna, 2021). However, ride-sharing demonstrated the ability to mitigate congestion when compared to traditional taxi services and dial-a-ride services. Thus, ridesharing may not be a suitable solution for addressing traffic issues in medium and small-scale cities. However, the dynamic ridesharing system exhibits the potential to notably enhance traffic conditions, particularly during peak hours for large-scale networks. In essence, the effectiveness of a ridesharing system in mitigating congestion appears to be closely linked to the presence of a critical mass of shareable trips capable of offsetting the additional distance created by the operational functioning of the service.

Uncertainties

The utilization of micromobility for transportation has fluctuated, notably during the pandemic. It experienced a substantial decline and is now in the process of recovery. These fluctuations underscore the potential for enhancing micromobility infrastructure and investing in operational improvements. For ridesharing, it may stimulate demand due to reduced travel times and costs, adding uncertainty to the future role of shared transport systems in congestion reduction.

Interaction Between Area, Subareas, and Other Areas

Shared transport systems and multimodal transportation are complementary concepts that can work together to enhance overall mobility and reduce congestion. They can cooperate in the areas of last-mile and first-mile connectivity, dynamic routing and flexibility, data sharing, and integration. As they cooperate, they can provide seamless connections, enhance flexibility and convenience, complement existing transit services, share data and insights, and promote sustainable mobility solutions. By leveraging the strengths of both concepts, cities can create more integrated, efficient, and user-centric transportation systems that meet the diverse needs of residents and visitors alike.

Telecommuting and Flexible Work Hours

This section provides a description of telecommuting and flexible work hours, emphasizing their potential in alleviating congestion. In addition, the summary incorporates an examination of both current and future technologies within the context of telecommuting.

Definition and Subareas

Definition

Telecommuting is a work arrangement when employees perform work elsewhere for at least some portion of their work schedule. Telework refers to the practice of working from a location other than the traditional office, often from home or another remote setting, using technology to stay connected and perform job duties (Texas A&M Transportation Institute, 2023b).

Flexible work hours, often referred to as flextime, provide employees with the flexibility to work within a specified time range during the day. This arrangement typically enables them to avoid peak traffic periods while ensuring all employees are present during a core period. For instance, an employer might establish work hours between 6:00 a.m. and 6:00 p.m., allowing employees to structure an eight-hour shift within this timeframe. Employees have the autonomy to set their own schedules, subject to approval (Texas A&M Transportation Institute, 2023a).

Subareas

Telecommuting Subareas:

- Full-time or regular telecommuting: In this arrangement, a worker dedicates each scheduled workday to remote work from a home office or another location like a coffee shop. Although occasional office visits may occur, the entirety of their work is conducted remotely.
- Hybrid telecommuting: In this approach, employees divide work time between home and the company's office. For example, employees might alternate weeks working from home and the office, work three days remotely and spend the remaining two days in the office, or have some employees work from the office and others from home.
- Temporary or special arrangement telecommuting: This form of telecommuting involves working remotely for a short duration, such as during inclement weather, a natural disaster, or while recovering from an illness.
- Freelance telecommuting: Predominantly embraced by freelancers or independent contractors who are not full-time employees of a company, this type of telecommuting offers flexibility and autonomy in work arrangements.

Flexible Work Hours Subareas:

- Staggered work-hour programs vary the arrival and departure times of employees, but employees may not choose their shift.
- A compressed week involves a distinct approach where an entire day is excluded from an employee's regular schedule. The hours from the omitted day are consolidated into longer workdays during the week. For example, employees might work four 10-hour days or complete 80 hours over nine days.

Congestion Reduction Strategies, Conditions, and Approaches

Congestion reduction strategies involving telecommuting and flexible work hours aim to alleviate traffic congestion by reducing the number of vehicles on the road during peak hours. Telecommuting allows employees to work remotely, reducing the need for daily commuting. Flexible work hours enable employees to stagger their schedules, avoiding peak traffic times. Success relies on supportive policies from employers and governments, technological infrastructure for remote work, and effective communication tools. These approaches offer benefits such as reduced commute times, lower carbon emissions, and improved work-life balance, contributing to more sustainable urban mobility. It is necessary to note that not every job can be done by telecommuting (Hopkins & Judith, 2019; Lari, 2012). Unlike telecommuting, flexible work hours can be more easily used by businesses that use shift work.

Current and Future Technologies

This congestion mitigation area, specifically in telecommuting, is heavily technology dependent. The main technologies used include the internet, smartphones, home computers, laptops, tablet computers, teleconferencing, and videoconferencing platforms (Lister & Harnish, 2019).

Benefits, Limitations, and Uncertainties

Benefits

Telecommuting and flexible work hours offer significant benefits in reducing traffic congestion. By allowing employees to work remotely, telecommuting eliminates the need for daily commuting, thereby reducing the number of vehicles on the road during peak traffic hours. Flexible work hours enable employees to stagger their schedules, spreading out the demand for transportation throughout the day and alleviating congestion during rush hours. These practices not only decrease commute times for those who still need to travel but also contribute to lower carbon emissions and improved air quality by reducing overall vehicle miles traveled. Additionally, telecommuting and flexible work arrangements can enhance employee productivity, job satisfaction, and work-life balance, leading to happier and more engaged workers. Overall, these strategies promote more sustainable urban mobility by easing traffic congestion and its associated environmental and social impacts.

Limitations

Limitations of telecommuting and flexible work hours include employer resistance, feasibility constraints in some industries, effectiveness variability based on adoption rates and local infrastructure, and inability to address all congestion causes like non-work travel or commercial transportation, limiting the overall impact on congestion reduction. Not every job can be done by telecommuting. A certain number of commuters cannot reasonably switch to telecommuting.

Uncertainties

An empirical study conducted in Sweden indicates that individuals who exclusively work remotely tend to travel less, according to the survey. Conversely, the opposite trend is observed for hybrid workers who engage in part-time remote work from home while also commuting to the workplace. The study's findings suggest that teleworking reduces travel demand. This reduction is attributed to the fact that more employees are fully telecommuting compared to those who work from the office and from home on the same day (Ellder, 2020).

Interaction Between Area, Subareas, and Other Areas

To further reduce congestion, telecommuting and flexible work hours, strategies can interact with other areas, especially with multimodal transportation, shared transport systems, congestion and road pricing, and smart navigation systems.

Smart Navigation Systems

In the modern era, GPS and smart navigation systems have revolutionized the way people navigate and explore cities. These technologies have become integral to our daily lives, assisting us in finding our way, optimizing travel routes, minimizing travel time, and discovering new places. Yet, these technologies have also had a profound effect on traffic patterns and congestion reduction.

Definition and Subareas

Smart navigation systems use GPS technology and vast amounts of user data to create maps showing real-time street and traffic conditions (Macfarlane, 2019b). Smart navigation systems can be separated into two categories. The first category encompasses smart navigation used by individuals, which includes smartphone applications like Waze, Google Maps, and Apple maps that can be used to create personalized, turn-by-turn directions to any location. The second category involves centralized managed systems that take a holistic view to maximize system efficiency, sometimes at the expense of individual travelers.

Congestion Reduction Strategies, Conditions, and Approaches

Most people encounter smart navigation systems through navigation apps on their smartphones. As of 2021, 85 percent of Americans owned a smartphone, and a Pew survey in 2015 found that 90 percent of Americans that owned smartphones got their driving directions from smart navigation apps at least some of the time (Madrigal, 2018). The permeation of smart navigation into everyday use has radically altered the ways that people travel through the city. Digital maps have made it easier to access new locations and services, while turn-by-turn directions have reduced navigational friction, expanding people's ability to drive, bike, or walk in unfamiliar or congested areas.

Real-time routing has become a central feature of smart navigation systems, with applications able to offer suggested routes to drivers to avoid backed-up corridors caused by crashes, construction, or daily congestion. Many of these apps were designed to eliminate traffic through routing algorithms.

Congestion reduction strategies utilizing smart navigation systems aim to alleviate traffic congestion through innovative approaches. These systems employ real-time traffic data and advanced algorithms to optimize routes, reduce travel times, and minimize congestion hotspots. Conditions for success include a robust technological infrastructure, reliable data sources, and effective integration with existing transportation networks. Approaches may involve dynamic rerouting based on traffic conditions, predictive analysis to anticipate congestion, and integration with public transit for seamless multimodal journeys. By leveraging smart navigation systems, cities can achieve more efficient traffic flow, improved air quality, and enhanced overall urban mobility.

However, there are scenarios where the use of smart navigation systems could potentially contribute to increased congestion. However, there are scenarios where the use of smart navigation systems could potentially contribute to increased congestion:

1. **Induced Demand:** By providing drivers with faster and more convenient routes, smart navigation systems may encourage more people to use their cars, leading to an increase in overall traffic volume (A. Bayen).
2. **Unintended Consequences:** In some cases, rerouting traffic away from congested areas may lead to increased traffic on alternative routes, potentially causing congestion in previously unaffected areas (Bliss, 2019).
3. **Data Inaccuracy:** If the data used by smart navigation systems is inaccurate or incomplete, it may result in suboptimal route recommendations or inefficient traffic management, potentially exacerbating congestion (Macfarlane, 2019a).

While these factors highlight potential challenges, it is important to note that smart navigation systems, when implemented effectively and integrated with broader transportation strategies, can play a crucial role in reducing traffic congestion and improving urban mobility overall.

Current and Future Technologies

Advances in GPS technology and data analytics have opened possibilities for more centrally managed transportation systems (Studies, 2023a).The technologies used in smart navigation systems include:

- Navigation apps on smartphones
- Smartphones
- GPS Technologies
- On-ramp metering lights
- Messaging signs
- Radio broadcasts

Benefits, Limitations, and Uncertainties

Benefits

A major benefit of using smart navigation systems to reduce traffic congestion is the optimization of travel routes in real time. By leveraging advanced algorithms and real-time traffic data, these systems can dynamically adjust routes to avoid congested areas, leading to reduced travel times and smoother traffic flow. Additionally, smart navigation systems can help distribute traffic more evenly across road networks, thereby minimizing congestion hotspots and improving overall road efficiency. This not only enhances the commuting experience for drivers but also reduces fuel consumption and emissions, contributing to a more sustainable urban environment.

Limitations

One limitation of using smart navigation systems to reduce traffic congestion is the reliance on accurate and up-to-date data. If the data used by the system is incomplete or inaccurate, it may lead to suboptimal route recommendations or ineffective congestion management. Additionally, there may be challenges in integrating smart navigation systems with existing infrastructure and transportation networks, especially in areas with limited technological resources or outdated infrastructure.

Uncertainties

The effectiveness of smart navigation systems may vary depending on factors such as user adoption rates, the accuracy of data sources, and the reliability of underlying technologies. Furthermore, there may be uncertainties related to the scalability and sustainability of smart navigation solutions, particularly in rapidly growing urban areas or regions with limited resources. Overall, while smart navigation systems hold promise for reducing congestion, there remain uncertainties about their long-term impacts and effectiveness in addressing complex urban mobility challenges.

Smart navigation systems pose a challenge to traffic managers due to their focus on individually optimized routes. Research suggests that when drivers prioritize their own routes, the transportation system operates below optimal levels, with 15–30 percent of total minutes lost in congestion (Çolak, Lima, & González, 2016).

Implementing a routing system that considers social benefits could save drivers one to three minutes on daily commutes, but some may experience longer commutes as a trade-off for overall efficiency.

Interaction Between Area, Subareas, and Other Areas

Smart navigation systems engage with various congestion alleviation domains such as connected and automated vehicles, public transportation systems, traffic incident management, and congestion pricing, potentially bolstering their efficacy in curbing traffic congestion.

Public Transportation (PT)

PT, including networks of buses, trains, and other shared transit options, plays a crucial role in reducing traffic congestion, especially in large and very large metropolitan areas. This section elaborates on PT and how it can help decrease traffic congestion. Present and future technologies are also considered.

Definition and Subareas

Definition

PT, also called transit, public transit, or mass transit, refers to regular and specialized transportation services, operating according to scheduled timetables, may require a fare, and are available to the public, but not including school buses, charter or sightseeing services (American Public Transportation Association, 2024). Public transportation systems are often implemented at the local or regional level.

Subareas

Subareas within PT systems encompass different types of transportation modes. The American Public Transportation Association (APTA) defines several modes of transportation which can be categorized into four groups: (1) bus, (2) train, (3) water transport, and (4) specialized transport (American Public Transportation Association, 2024).

Details on each subarea are provided below.

1. **Bus** is a transit service mode characterized by vehicles powered by diesel, gasoline, battery, or alternative fuel engines. Buses operate on streets and roadways in fixed-route or other regular service. Types of buses:
    - Local service vehicles: may stop every block or two along a route several miles long. When limited to a small geographic area or to short-distance trips, local service is often called circulator, feeder, neighborhood, trolley, or shuttle service.
    - Bus rapid transit (BRT) is a bus-based alternative to metro and tram systems, which offers stations and features that speed up boarding and improve rider experience: real time arrival screens, off-board ticketing, dedicated lanes, priority at intersections, and features to enhance speed and efficiency (Figure 13).

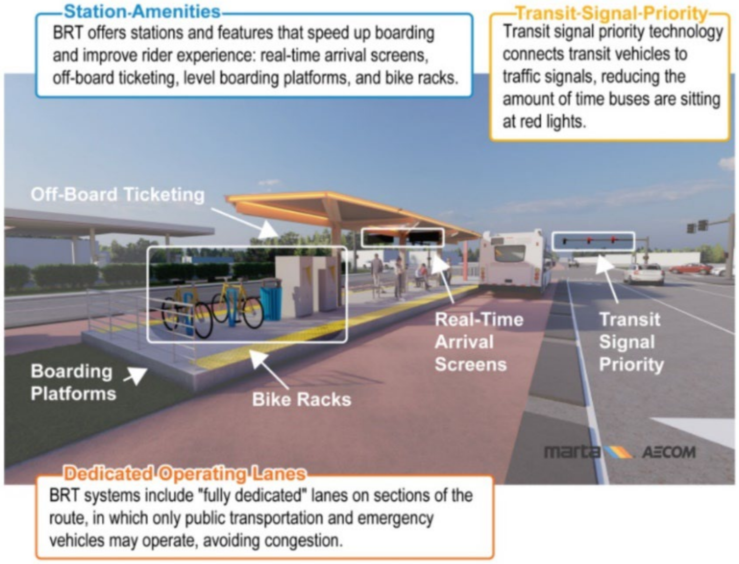


Figure 13. Example of BRT elements.

Source: (https://connectclayton.com/what-is-brt/)

2. **Train** is a transit service mode represented by a connected series of vehicles that move along a set of tracks or rails for the purpose of transporting passengers, freight, or both.
   - **Commuter Train** is a mode of transit service (also called metropolitan rail, regional rail, or suburban rail) for short-distance travel between central cities and nearby suburbs. They operate regularly, typically under transit operator contracts, providing transportation within urbanized areas. These services use electric or diesel propulsion and offer multi-trip tickets, specific fares, and limited central business district stations, often on freight railroad routes, excluding intercity rail except for commuter segments.
   - **Light Rail** is a mode of transit service (also called streetcar, tramway, or trolley) operating passenger rail cars singly (or in short, usually two-car or three-car, trains) on fixed rails in right-of-way that is often separated from other traffic for part or much of the way. Light rail vehicles are typically driven electrically with power being drawn from an overhead electric line via a trolley or a pantograph, driven by an operator on board the vehicle, and may have either high platform loading or low-level boarding using steps.
   - **Heavy Rail** is a mode of transit service (also called metro, subway, rapid transit, or rapid rail) operating on an electric railway with the capacity for a heavy volume of traffic. It is characterized by high speed and rapid acceleration passenger rail cars operating singly or in multi-car trains on fixed rails; separate rights-of-way from which all other vehicular and foot traffic are excluded; sophisticated signaling, and high platform loading.
   - **Cable Car** is a railway with individually controlled transit vehicles attached while moving to a moving cable located below the street surface and powered by engines or motors at a central location not on board the vehicle.
3. Specialized Services
   - **Paratransit** means customized transportation services for individuals with disabilities, often using small vehicles or vans. Vehicles do not operate on a fixed route or schedule.

- **Carpooling/Vanpooling** is ridesharing by prearrangement using vans or small buses providing round-trip transportation between prearranged boarding points and a common destination. Vehicles must comply with mass transit rules, including ADA provisions, and be open to the public.

4. Water Transport

   - **Ferry Boat** is a transit mode using vessels to carry passengers and, in some cases, vehicles over water. Generally, steam or diesel-powered, urban ferryboat service involves at least one terminal within an urbanized area. International, rural, island, and urban park ferries are excluded.

Congestion Reduction Strategies, Conditions, and Approaches

Public transportation offers an alternative to driving and has the potential to address congestion by accommodating a greater number of passengers than individual cars, making it a key solution to alleviating traffic issues. A combination of convenience, affordability, and reliability can make it an effective tool in reducing traffic congestion. Certain conditions must be met for public transportation to attract more riders and be effective in reducing congestion, for example (Nguyen-Phuoc, Young, Currie, & Gruyter, 2020; Redman, Friman, Garling, & Harting, 2013; Rubin & Mansour, 2013):

- **Comprehensive Network:** A well-developed public transportation network that covers a wide geographic area and provides convenient access to various destinations encourages people to choose transit over private vehicles.
- **Integrated Transportation Planning:** Coordination and integration between different modes of transportation, such as buses, trains, and bicycles, enhance the overall efficiency of the transportation system. Integrated planning ensures seamless connections and makes public transportation a more attractive option.
- **Reliability and Frequency:** Public transportation services need to be reliable and frequent to draw commuters. Readily available public transportation that adheres to schedule will likely attract more people willing to rely on it for their daily commutes, reducing the need for individual car trips.
- **Affordability:** Affordable and competitive pricing for public transit fares compared to the cost of owning and maintaining a private vehicle can encourage people to use public transportation.
- **Park-and-Ride Facilities:** Providing park-and-ride facilities at transit hubs allows commuters to leave their cars at convenient locations and switch to public transit for the rest of their journey. This reduces the number of private vehicles entering urban centers.
- **Congestion Pricing:** Implementing congestion pricing, where fees are imposed on vehicles entering congested areas during peak hours, can incentivize people to use public transit instead of driving, leading to reduced traffic in city centers.
- **Land Use Planning:** Urban planning that encourages higher population density around transit hubs and mixed-use developments can contribute to increased public transit ridership. This reduces the need for long-distance car commutes.
- **Environmental Awareness:** Public awareness campaigns highlighting the environmental benefits of using public transportation, such as reduced air pollution and lower carbon emissions, can influence individuals to opt for more sustainable transportation options.
- **Government Policies and Incentives:** Supportive government policies, subsidies, and incentives for public transit operators can contribute to developing and maintaining efficient and attractive public transportation systems.

BRT featuring segregated lanes has emerged as a favored mass public transport strategy, proving effective in alleviating traffic congestion. This approach is pragmatic, demands lower capital investment and development time, and offers an integrated network that ensures safer, faster, affordable, and more efficient transportation.

Well-designed, consistent, and reliable public transport services can help address recurring congestion, especially in urban areas where traffic congestion is a chronic issue. This can be achieved by aligning the routes with high-demand areas and employment centers. In addition, adequate service frequency and capacity during peak commuting hours help manage recurring congestion when traffic congestion is most severe.

Public transportation systems can also address non-recurring congestion. Public transit systems can offer alternative routes or services to bypass the affected areas during incidents like crashes or road closures. Public transportation agencies can adjust service routes or schedules in response to special (like sports games or festivals) or emergency events to accommodate changes in demand or reroute services to avoid affected areas.

Current and Future Technologies

Current technologies used in public transportation systems include innovations to improve efficiency, safety, accessibility, and sustainability, including automated fare collection, real-time passenger information systems, accessibility features, vehicle tracking and management, on-board Wi-Fi, and ITS. In the future, advancements are expected in the highlighted technologies, as well as in CAV technologies, MaaS platforms, and the integration of IoT devices into transportation infrastructure. Additionally, data analytics and predictive modeling will be more critical for transportation planners. In the next two decades and beyond, the evolution of public transportation might include urban air mobility, fully autonomous transit, advanced high-speed rail, and hyperloop technologies (Mohammed & Oke, 2023; Nalmpantis, Roukouni, Genitsaris, Stamelou, & Naniopoulos, 2019).

Benefits, Limitations, and Uncertainties

Benefits

The primary advantage of PT systems in mitigating road congestion is providing viable alternatives to private vehicle use and removing a substantial number of individual vehicles from the roads. When more people choose public transit options, these systems effectively reduce overall traffic volume and improve traffic flow, especially in large and very large metropolitan areas. In cities where public transit is robust and widely used, traffic congestion reduction percentages can range from 10 percent to as high as 30 percent or more during peak hours. Additionally, PT has relatively low crash rates per unit of travel. Inter-city and commuter passengers comprise about 1/20th, urban rail passengers comprise about 1/30th, and bus passengers comprise about 1/60th of the traffic fatalities per 100 million passenger miles compared to automobile travel. The differences in passenger fatalities between private and public vehicles are presented in Table 3.

Table 3. Passenger Fatalities per Billion Passenger Miles (2000–2009)

Travel Mode	Deaths per Billion Passenger-Miles
Car or light truck driver or passenger	7.28
Commuter rail and Amtrak	0.43
Urban mass transit rail (subway or light rail)	0.24
Bus (transit, intercity, school, charter)	0.11
Commercial aviation	0.07

Source: (Savage, 2013)

Limitations

PT, while effective in many ways, also faces limitations in mitigating traffic congestion (Rubin & Mansour, 2013):

- Limited coverage and accessibility: PT may not reach all areas, mainly suburban or remote regions, making it challenging for some individuals to rely solely on public transportation for their commute.
- Frequency and reliability: long wait times between services or inconsistent schedules can discourage people from using PT and encourage them to opt for personal vehicles.
- First and last-mile connectivity: difficulty accessing transit stops or stations from home or work (first-last mile challenge) can deter commuters from using public transit, leading to continued reliance on personal vehicles.
- Perception and cultural preferences: cultural factors and perceptions about public transit, such as perceived inconvenience, discomfort, or safety concerns, may deter some individuals from utilizing these services regularly.
- Limited flexibility connectivity: PT routes are often fixed, and passengers may need to transfer between multiple modes or lines to reach their destinations, which can be less convenient compared to direct routes by private vehicles.

Uncertainties

There is no clear consensus on whether the PT reduces congestion or not. Extensive research in transportation and economics suggests that public transit minimally alleviates congestion, raising concerns about its substantial subsidy rate. However, researchers (M. Anderson, 2013) stated that the choices made by PT users have notably high impacts on congestion. Using the data from the 2003 strike by Los Angeles transit workers and applying a regression design discontinuity, they observed a 47 percent increase in average highway delay when transit service stopped operating due to the strike. This indicates that the net benefits of transit systems may be more significant than some may suggest.

Another uncertainty is urban planning, including land use patterns and zoning regulations, which might influence the accessibility and availability of PT services. High-density land use patterns tend to support more efficient PT, and the mix of land uses influences travel behavior and demand for PT. Zoning regulations determine the allowable land uses and densities in cities and regions and, therefore, influence the potential success of PT.

Interaction Between Area, Subareas, and Other Areas

There is a strong interaction between subareas in PT congestion reduction areas. A well-designed system facilitates seamless mode switching for riders, ensuring easy accessibility. PT strategies interact with most of the other areas considered in this report. However, they are highly interconnected with Smart and Advanced Signal Timing and Optimization Systems, Congestion and Road Pricing, Shared Transportation Systems, and Smart Navigation Systems.

Congestion and Road Pricing

This section reviews congestion and road pricing. It delivers definitions of congestion and road pricing, highlighting their potential in mitigating congestion. Additionally, the summary integrates an exploration of both current and future technologies within the scope of congestion and road pricing.

Definition and Subareas

Definition

Congestion pricing is a system where motorists are charged a fee for driving in designated areas or during peak hours, aimed at reducing traffic congestion and encouraging the use of alternative modes of transportation. Congestion pricing works by shifting some less critical or more discretionary rush-hour highway travel to other transportation modes or to off-peak periods, taking advantage of the fact that most rush-hour drivers on a typical urban highway are not commuters.

Road pricing involves charging a fee for access to use and use of a lane, road, area or regional network for the purpose of generating revenue, managing traffic congestion or both (Federal Highway Administration, 2008). The aim of road pricing is to target imbalanced traffic flow and to manage transportation demand. By charging drivers to use congested roads during peak hours, road pricing can incentivize people to travel during off-peak times, use alternative modes of transportation, or carpool, thereby reducing overall congestion levels. Additionally, the revenue generated from road pricing can be used to fund transportation infrastructure improvements or other initiatives aimed at reducing congestion.

Subareas

The following sub areas fall under the umbrella of both congestion and road pricing**:**

- **Variably priced lanes** include express toll lanes and high-occupancy toll (HOT) lanes. On HOT lanes, low-occupancy vehicles are charged a toll, whereas high-occupancy vehicles (HOVs), public transit buses, and emergency vehicles are allowed to use the lanes free of charge or at reduced rates.
- **Variable tolls on roadways** is a system where the flat toll rates on existing toll roads are changed to a variable toll schedule so that the toll is higher during peak travel hours and lower during off-peak or shoulder hours. This encourages motorists to use the roadway during less congested periods and allows traffic to flow more freely during peak times.
- **Zone-based or cordon pricing** involves charging a fee to enter or drive within a congested area, usually a city center.

- **Area-wide or system-wide pricing** involves per-mile charges, which the government will consider using as a replacement for fuel taxes in the future. A congestion-pricing component was tested, with higher charges during congested periods on high-traffic road segments.

Congestion Reduction Strategies, Conditions, and Approaches

Congestion reduction strategies incorporate a variety of measures aimed at alleviating traffic congestion, a persistent issue in urban areas. Among these strategies, congestion and road pricing have gained attention for their potential effectiveness. By implementing tolls or fees for vehicle usage during peak hours or in congested zones, road pricing aims to regulate demand and encourage alternative transportation modes or off-peak travel. This approach not only helps manage traffic flow by incentivizing behavior changes among commuters but also serves as a revenue source for infrastructure development. Moreover, congestion pricing can be tailored to specific conditions and locations, allowing for flexibility in implementation. However, successful deployment relies on effective communication, stakeholder engagement, and consideration of equity concerns to ensure fair access to transportation options for all segments of society.

Congestion and road pricing can be implemented on various types of roads, including arterials, highways, expressways, and urban streets.

- Congestion and road pricing on arterial roads can help manage traffic congestion during peak hours by encouraging mode shift, optimizing road usage, and generating revenue for transportation investments. Arterial congestion pricing may involve tolling specific segments of the road or implementing variable tolling based on traffic conditions.
- Congestion and road pricing on expressways and highways can address congestion hotspots, bottlenecks, or chokepoints by managing demand for limited road capacity. Variable tolling or dynamic pricing strategies can be used to regulate traffic flow and maintain optimal speeds, particularly during peak travel times or in high-demand areas.
- Congestion and road pricing may be applied to urban streets, downtown cores, or specific zones with high levels of vehicular traffic and limited road space. By charging fees for vehicle access to congested urban areas, congestion pricing can incentivize alternative modes of transportation, reduce vehicle miles traveled, and improve overall mobility and air quality in urban centers.
- Congestion pricing and road pricing can also be implemented along transit corridors, where high volumes of transit vehicles, pedestrians, and cyclists coexist with motorized traffic. Pricing strategies may prioritize transit, active transportation, and sustainable mobility options, while managing congestion and improving safety for all road users along busy transit routes.

Current and Future Technologies

Congestion and road pricing rely on various technologies to accurately measure and manage traffic flow, enforce pricing policies, and provide real-time information to drivers. The technologies include:

- **Automatic License Plate Recognition (ALPR)**: The use of cameras to capture images of license plates of vehicles entering or traveling within a congestion pricing zone. These cameras enable authorities to identify vehicles and enforce congestion and road pricing regulations by associating license plate data with registered accounts or toll payments.

- **Electronic Toll Collection (ETC)**: The use of electronic transponders or vehicle-mounted RFID tags to automatically collect tolls from vehicles as they pass through tolling points or congestion and road pricing gantries. ETC eliminates the need for manual toll collection, enabling seamless and efficient payment processing.
- **GPS and Location-Based Services**: These are crucial in congestion and road pricing by providing real-time vehicle tracking, route guidance, and navigation assistance. GPS-enabled devices and mobile applications help drivers navigate congestion and road pricing zones, access pricing information, and choose alternative routes to avoid congestion.
- **Dynamic Pricing Algorithms**: These use real-time traffic data, congestion patterns, and demand forecasts to adjust toll rates dynamically based on current traffic conditions and supply-demand dynamics. These algorithms optimize pricing strategies to manage congestion, maximize road capacity utilization, and balance traffic flow across different time periods and road segments.
- **Traffic Surveillance and Monitoring Systems**: These include CCTV cameras, loop detectors, radar sensors, and Bluetooth beacons to collect data on traffic volume, speed, density, and occupancy. These systems provide valuable insights into traffic patterns, congestion hotspots, and travel behavior, enabling authorities to make informed decisions about congestion pricing policies and operational strategies.
- **Payment and Account Management Systems**: These facilitate the collection of tolls, fees, or charges from drivers using congestion-priced roads or zones. These systems support various payment methods, including prepaid accounts, credit/debit cards, mobile payments, and electronic wallets, while ensuring secure and reliable transaction processing.
- **Information and Communication Technologies (ICT)**: Technologies such as roadside message signs, variable message signs (VMS), mobile apps, websites, and digital platforms disseminate real-time information to drivers about congestion pricing policies, toll rates, road conditions, alternative routes, and travel advisories. These communication channels enhance driver awareness, encourage mode shift, and promote behavioral changes to reduce congestion.

In the near future, the current technologies will be improved, and, in the long-term future, it is expected to have more technologies involved with:

- **CAV** technologies will play a significant role in congestion road pricing by enabling automated V2I communication and cooperative driving capabilities. CAVs will interact with congestion pricing systems to receive real-time pricing information, plan optimal routes, and adjust travel behavior based on pricing incentives, leading to more efficient use of road capacity and smoother traffic flow.
- **Blockchain and Distributed Ledger Technology (DLT)** will enhance the security, transparency, and integrity of congestion pricing transactions, payment settlements, and data management. These technologies will support tamper-proof record-keeping, decentralized authentication, and smart contracts for automated toll collection, revenue distribution, and audit trails, ensuring trust and accountability in congestion pricing operations.
- **Big Data and Predictive Analytics** will enable congestion pricing authorities to harness large volumes of real-time traffic data, user behavior data, and spatial-temporal information to optimize pricing strategies, identify congestion hotspots, and forecast future traffic conditions.
- **AI and ML** will be deployed to develop sophisticated traffic prediction models, adaptive pricing algorithms, and personalized mobility solutions tailored to individual traveler preferences and behavior patterns. AI-driven congestion management systems will continuously learn from real-world data,

adapt to changing conditions, and optimize pricing mechanisms to achieve desired traffic management outcomes.

- **Privacy-Preserving Technologies** such as differential privacy, homomorphic encryption, and federated learning will be essential to safeguard personal privacy, anonymity, and data confidentiality. These technologies will enable congestion pricing authorities to extract valuable insights from aggregated data while protecting individual privacy rights and compliance with data protection regulations.

Benefits, Limitations, and Uncertainties

Benefits

Implementing congestion and road pricing in large or very large metropolitan areas offers a multifaceted approach to tackling traffic congestion. By charging vehicles for their usage during peak hours or in congested zones, these pricing mechanisms incentivize commuters to shift their travel behaviors, leading to reduced traffic volumes, smoother traffic flow, and shorter travel times. The revenue generated can be reinvested in transportation infrastructure improvements, such as enhancing public transit systems and expanding alternative transportation options, thereby fostering more sustainable and efficient urban mobility. Additionally, congestion pricing can help address equity concerns by offering discounts for low-income residents and funding initiatives to improve transportation accessibility for underserved communities. Overall, congestion and road pricing not only alleviate congestion but also promote environmental sustainability, economic vitality, and social equity in large metropolitan areas.

Limitations

Congestion and road pricing pose some limitations in congestion reduction. One of the issues involves implementation cost. Designing, implementing, and operating congestion pricing systems can be complex and resource-intensive, requiring significant investments in technology, infrastructure, enforcement, administration, and public outreach.

Uncertainties

The main uncertainty includes equity concerns as it can disproportionately impact low-income and disadvantaged communities. Critics argue that pricing schemes may create barriers to access for those who rely on private vehicles due to limited transportation options or financial constraints, exacerbating social inequities in access to mobility. Additionally, the success of congestion pricing relies on drivers' willingness to change their travel behavior in response to pricing incentives. However, some drivers may be resistant to shifting their travel patterns or modes of transportation, especially if viable alternatives are limited or perceived as less convenient or reliable.

Interaction Between Area, Subareas, and Other Areas

The successful implementation of congestion and road pricing is closely intertwined with the efficiency and reliability of public transportation systems, advanced traffic signal timing and optimization systems, and TSM&O strategies. Public transportation serves as a viable alternative for commuters incentivized to shift from private vehicles due to congestion pricing, necessitating robust transit networks with increased capacity and reliability. Advanced traffic signal timing optimizes traffic flow by dynamically adjusting signal patterns to accommodate changing demand, complementing congestion pricing efforts by maximizing the efficiency of road usage. Additionally, TSM&O strategies, such as incident management and real-time traffic monitoring, play a pivotal role in mitigating congestion by promptly addressing incidents and proactively managing traffic flow. Together, these interconnected elements synergize to enhance the effectiveness of congestion and road pricing initiatives, ultimately leading to more efficient and sustainable urban transportation systems.

Connected and Automated Vehicles (CAVs)

The advancement and popularity of CAVs have surged due to rapid technological innovation and growing consumer demand for safer, more efficient transportation solutions. This section provides insights from a literature review on CAVs, highlighting their potential to reduce or increase traffic congestion. The way CAVs can evolve in the future is also highlighted.

Definition and Subareas

There are various definitions of connected and automated vehicles, with some of the simplest presented below.

Connected Vehicles

Connected vehicles are driverless vehicles that connect with each other and the traffic management systems (Neufville, Abdalla, & Abbas, 2022).

Automated Vehicles

Automated vehicles are vehicles that will no longer need a traditional driver in the future (NHTSA); thus, those vehicles can drive by themselves. Different levels of automation exist as described in Figure 14. Although current vehicles have some levels of automation, fully automated vehicles are yet to be created.

Connected and Automated Vehicles

Connected automated vehicles are vehicles that combine autonomous driving capabilities with communication technologies, enabling them to interact with other vehicles, infrastructure, and the surrounding environment for enhanced safety, efficiency, and convenience.

Subareas

CAVs can be subdivided into connected vehicles and autonomous vehicles as described earlier. When combined, they can further be grouped into private CAVs and shared CAVs. Private CAVs refer to connected automated vehicles that are owned or leased by individuals or organizations for personal use, while shared CAVs are those operated by transportation services or fleets, allowing multiple users to access and utilize them for travel on a shared basis, often through ride-hailing or ride-sharing platforms.

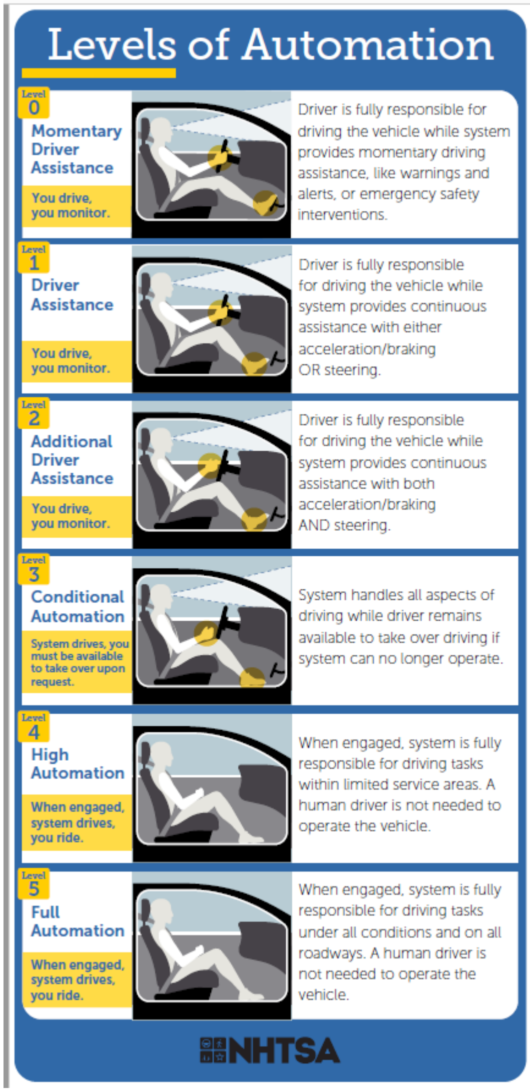


Figure 14. Levels of automation.

Source: (NHTSA, n.d.)

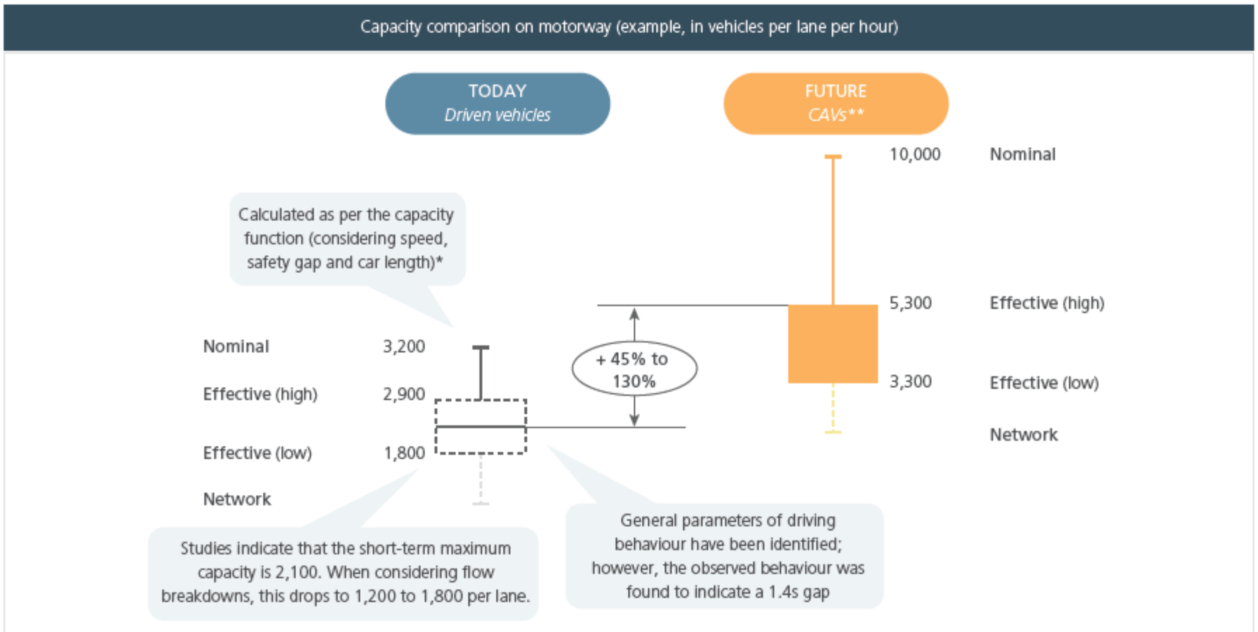
Congestion Reduction Strategies, Conditions, and Approaches

CAVs can help reduce congestion in several ways. For example, it has been stated that CAVs will be more efficient, use less space, and reduce crashes (Circella, Jaller, Sun, Qian, & Alemi, 2022). Some of the areas in which CAVs can assist with congestion are highlighted in this section.

Vehicle Headways, and Roadway Capacity

CAVs can enhance roadway capacity by reducing vehicle headways (from 0.9 to 0.2 seconds).
CAVs are anticipated to enhance roadway capacity by reducing the headway between vehicles from 0.9 to 0.2 seconds (Barrett, Streeting, & Khanna, 2019). To understand the effect of that change, when headway between vehicles is reduced to 0.5 seconds (minimum tolerable safety gap based on research), researchers anticipate the roadway capacity to reach 3,300 to 5,300 vehicles per lane hour (see Figure 15). As a result, the change in capacity when vehicle headway shifts from 0.9 to 0.5 is equivalent to an increase of 45 percent to 130 percent

vehicles per lane hour. Although this can be a big change, it will not be comparable to the potential improvement in capacity by CAVs when vehicle headway is reduced to 0.2 seconds (Barrett et al., 2019). Many other sources anticipate about a 60 to 80 percent increase in vehicles per lane hour when CAVs are fully adopted (Barrett et al., 2019). Thus, it can be stated that vehicle platooning of Connected Fully Autonomous Vehicles (ConFAVs) will enhance roadway capacity (Neufville et al., 2022).



Note: * Other environmental factors relevant to determine effective capacity are not considered; ** Assuming full penetration
Source: RMS; University of Columbia; University of Southampton; L.E.K. research & analysis

Figure 15. Capacity comparison.

Source: (Barrett et al., 2019)

Non-recurring Congestion, and Safety

CAVs can reduce non-recurring congestion through the reduction of human errors and related crashes.
CAVs can reduce non-recurring congestion through the reduction of human errors, which is a major cause of roadway crashes (Barrett et al., 2019; NHTSA). Full automation may provide transformative safety opportunities and reduce non-recurring congestion. These systems may act faster than drivers in case of emergencies (NHTSA). CAVs can also reduce the stop-and-go traffic issue faced by traditional vehicles. This change can improve traffic flow, safety, and enable consistent speed and distance between vehicles (Bayen, 2021).

Private and Shared CAVs

Whether CAVs are privately owned, or part of pooled rides may have an impact on congestion.
A CAV that is part of a commercial fleet (e.g., shared ride-hailing fleets) that enables **pooled rides** may reduce congestion (Barrett et al., 2019; Circella et al., 2022). On the other hand, private CAVs can increase vehicle miles traveled by 38 percent due to induced demand and deadheading (Figure 16).

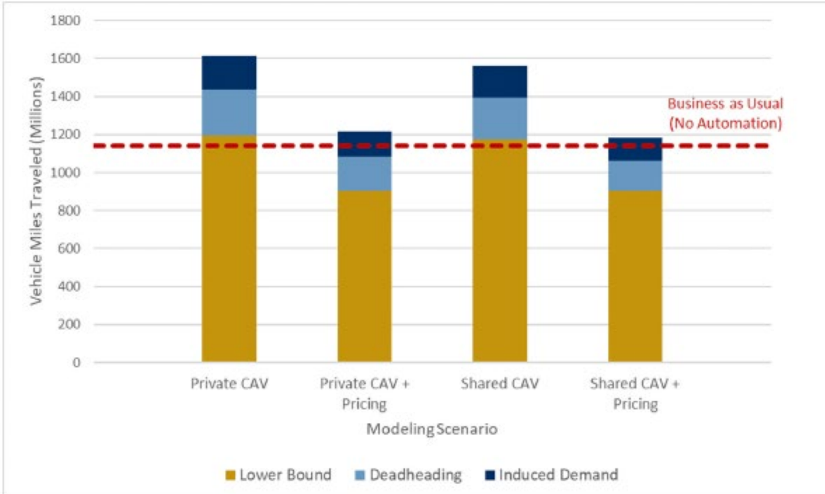


Figure 16. Vehicle miles traveled across four scenarios.

Source: (Circella et al., 2022)

Mode Choice, and Roadway Pricing

Some authors indicate that CAVs will affect mode choice, travel destinations, travel distances, and congestion (Circella et al., 2022; Simoni, Kockelman, Gurumurthy, & Bischoff, 2019). They believe that private CAVs will lead to a significant shift from transit to automobiles, which will also decrease the use of active transportation (e.g., walking and bicycling). The mode shifts and the fact that some CAVs may travel empty (deadheading) in the future will cause an increase in vehicle-miles traveled (VMT) and traffic delays (Simoni et al., 2019). Up to now, it is uncertain whether CAVs can help with recurring congestion.

The advantages of improved accessibility and traffic flows may counteract with the drawbacks of more trip-making and longer distances traveled (Simoni et al., 2019).
Congestion pricing (CP) and road tolls are mentioned as effective tools for reducing CAVs-related vehicle miles traveled and other negative costs of traffic congestion (Circella et al., 2022; Simoni et al., 2019). In addition, programs favoring shared CAVs instead of private CAVs, making CAVs connect travelers to transit services, and encouraging fast vehicle electrification can help reduce the negative effects of CAVs (Circella et al., 2022).

Land Use

CAVs will possibly cause land use changes, such as increased suburban sprawl if commuters live further from employment centers (Circella et al., 2022). Consequently, planning and coordination of land use development may be important to prevent suburban sprawl caused by CAVs.

Public Acceptance, and Policy Intervention

The abundant deployment of CAVs will depend on customer acceptance and willingness to purchase the vehicles (Neufville et al., 2022). For example, some authors listed important factors to consider for CAVs to reduce roadway congestion and enhance urban mobility (Barrett et al., 2019), including:

- Government incentives, regulations, and the role of policymakers
- Consumer social behavior and changing preferences
- Availability of substitute modes of transport

Other authors indicate that low penetration rates of shared AVs can create more congestion if not regulated. This effect is anticipated for shared AVs (SAVs). SAVs can create blockages and queues on low-capacity links when implemented at low penetration rates or when less than 25 percent of travelers are using the systems. Regulating drop-off locations of SAVs and network circulation will be needed in the future. The negative effects of SAVs could be overcome at higher penetration rates. It will also be important to separate SAV traffic from traditional traffic to get full benefits (Overtoom, Correia, Huang, & Verbraeck, 2020).

Benefits, Limitations, and Uncertainties

CAVs have many promising features. Despite the known benefits of CAVs, the technologies have limitations. As mentioned previously, uncertainties exist about whether the benefits of CAVs will surpass the limitations. This section elaborates on some benefits and limitations, as well as the uncertainties.

Benefits

The largest benefit of CAVs in reducing traffic congestion lies in their ability to optimize traffic flow through real-time communication and coordination, thereby significantly reducing the frequency of traffic incidents, minimizing stop-and-go patterns, and efficiently utilizing road space, ultimately leading to smoother traffic flow and reduced congestion.

- Penetration of large volumes of connected fully autonomous vehicles (ConFAVs) have the potential to **decrease average delays by up to 100 percent** (Neufville et al., 2022; Zhao, Malikopoulos, & Rios-Torres, 2019).
- By eliminating or mitigating common human errors such as distracted driving, speeding, and following too closely, CAVs can significantly enhance safety on the roads, and **prevent a significant portion of traffic crashes**.
- **Platooning can improve mobility and increase capacity** due to shorter headways. It can also reduce fuel consumption, travel time, and improve traffic safety (Barrett et al., 2019).
- **CAVs could address equity** in the future by improving the mobility of vulnerable populations (disabled, children, elderly, people without driver licenses, etc.) (Neufville et al., 2022; NHTSA).

Limitations

CAVS can create new trips (induced demand) and increase traffic volume by 10 to 25 percent (but could address equity).
CAVs can lead to new demand (new trips) for the roadways that can increase traffic volume by 10 percent to 25 percent by 2060 (Barrett et al., 2019). For example, people without driver licenses and those who are enabled to drive could all be single passengers in CAVs. Although this could be considered among the great benefits of CAVs (especially related to equity) (Neufville et al., 2022; NHTSA), it could counteract the gain of capacity from the decrease in headways highlighted previously (Barrett et al., 2019). Specifically, the authors highlighted that discretionary leisure trips will escalate by 5 to 20 percent (Barrett et al., 2019). Induced demand could lead to a 5 to 15 percent increase in average vehicle trips per person compared with current levels.

At low-penetration rates and when SAVs are not separated from traditional traffic, it can create bottlenecks during curbside drop-off.
When not separated from traditional traffic at lower penetration rates, SAVs (Shared Automatic vehicles) can create future challenges when stopping on the curbside to drop off passengers. This will be another source of bottlenecks for other road users using those links (Overtoom et al., 2020).

Lack of proper regulations may be problematic and lead to more trips and congestion.
Issues with the lack of regulations for CAVs include regulations on children riding alone and people preferring to ride their private vehicles instead of shared vehicles (Barrett et al., 2019). In a paper, it was predicted that the intensity of education trips might multiply by 100 percent because instead of dropping their kids off to school on their way to work, parents may decide to make their children ride a separate CAV (Figure 17). Without proper regulations, CAVS could also lead to multiple trips that could be done in trip chaining (Barrett et al., 2019).

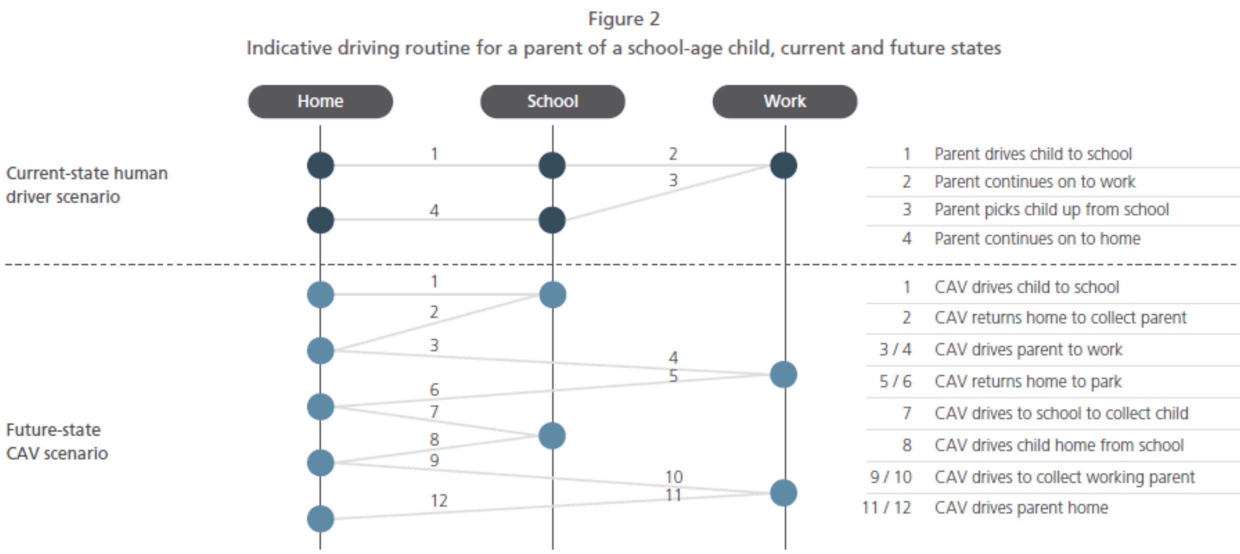


Figure 17. Indicative driving for a parent of a school-age child, current and future states.

Source: (Barrett et al., 2019)

Uncertainties

The literature is uncertain whether CAVs will help reduce congestion or exacerbate it (Barrett et al., 2019). In the area of recurring congestion, some authors are not clear whether new and non-necessary trips that will be generated because of CAVs may neutralize the efficiency benefits they may bring. Things like deadheading and single passenger trips may alter the potential benefits.

Current and Future Technologies

CAVs use many technologies that will continue to evolve in the future. For example, current automated vehicles "use radar and vision sensors to warn drivers of a range of hazards, alerting them to sudden braking ahead, collision paths, deviations toward the road edge, sharp curves, slippery patches, lane closures, and risks of overturning" (Neufville et al., 2022). Once the problem is identified, the systems trigger defense strategies to avoid the dangers with warning messages sent to the driver or through the automatic correction of vehicular operations, such as automatic braking or lane correction (Neufville et al., 2022). Technologies for lane-changing maneuvers of CAVs could also assist with congestion reduction in the future (Neufville et al., 2022).

National Highway Traffic Safety Administration (NHTSA) has predicted the evolution of vehicle automation, which is demonstrated in Figure 18.

Figure 18. Five eras of safety.

Source: (NHTSA)

Interaction Between Area, Subareas, and Other Areas

CAVs interact with many areas and subareas in this report. A few examples of the interaction between CAVs and other areas and subareas are described next.

- **CAVs can reduce the usage of tolled roadways (Interaction with TSM&O)**: With CAVs, people may be less sensitive to travel time and be productive during that time. This level of ease can make tolled roadways unfavorable (Barrett et al., 2019). At the same time, road pricing may be necessary for a successful CAV implementation, as discussed previously.

- **CAVs can boost the acceptance of shared rides (Interaction with shared transportation systems)**: CAVs can boost acceptance of shared/pooled transportation (Barrett et al., 2019; NHTSA).
- **CAVs and smart and advanced signal timing and Optimization are linked.** Data from CAVs can be used to optimize smart signals.
- **Other emergent technologies can disrupt the adoption of CAVs (Interaction with other emergent technologies):** Other emerging technologies and transformative modes, including unmanned aerial vehicles and Hyperloop transportation systems, could significantly disturb the adoption of CAVs and change the sources of roadway congestion (Barrett et al., 2019).

Advanced Transportation Technologies

This section summarizes the literature review on advanced transportation technologies. It includes different transportation technologies, their effects on congestion reduction, congestion reduction strategies, conditions, and approaches, as well as their benefits, limitations, and uncertainties.

Definition and Subareas

Advanced transportation technologies involve using cutting-edge technologies and systems to address traffic congestion, improve safety, and enhance traffic flow. They utilize automation, electrification, infrastructure design, and other technologies to manage traffic and offer alternative modes of transportation. These technologies have undergone major development and are being implemented at a significant scale.

Subareas or examples of advanced transportation technologies comprise autonomous vehicles (AVs), smart traffic management systems, EVs, UAVs, high-speed rail, and eVTOL. Since there are separate sections on CAVs and smart traffic management systems, this section focuses on UAVs and high-speed rails. eVTOL will be briefly introduced.

UAV, commonly referred to as a drone, represents an aircraft devoid of a human pilot, crew, or passengers. Presently, UAVs find applications across various domains, and their potential extends to the objective of mitigating congestion, primarily through the transportation of goods and the utilization of drones for traffic management.

High-speed rail (HSR) is a type of rail transport network that utilizes trains that run significantly faster than those of traditional rail, using an integrated system of specialized rolling stock and dedicated tracks. These trains are designed to travel at speeds typically exceeding 250 kilometers per hour (155 miles per hour) and often reach speeds well above this threshold ("General Definition of High-speed").

eVTOL aircraft are in advanced development and testing stages but are not yet widely available for public use. Companies like Joby Aviation, Archer Aviation, Lilium, and Vertical Aerospace are focusing on applications such as urban air mobility, cargo transport, and emergency services. Certification by aviation authorities like the FAA and EASA is underway, with several manufacturers nearing approval. Prototypes have undergone extensive testing, and some companies aim to begin commercial services in the coming years, particularly in urban areas with supporting infrastructure. However, widespread adoption will depend on regulatory approval, public acceptance, and the development of vertiports and charging facilities.

Congestion Reduction Strategies, Conditions, and Approaches

UAVs

UAVs can help address congestion in several ways as described next.

UAVs and Last-Mile Delivery

The idea of using UAVs or drones for last-mile delivery is gaining popularity. Employing drones for parcel delivery shows promise in reducing expenses by removing the need for drivers or trucks, cutting congestion costs, and minimizing missed deliveries due to its rapid 30-minute dispatch-to-delivery window (Jean-Philippe Aurambout, 2019). The implementation of drone delivery has the potential to diminish the requirement for local transport, leading to a reduction in congestion and air emissions. However, concerns about the safety and noise from drones have been raised ("Bladeless Drones,").

UAVs and Emergency Response

The deployment of drones as first responders, abbreviated as DFR, stands out as one of the most influential use cases. This innovation has reshaped the operations of emergency services, leading to substantial enhancements in response times and safety outcomes. In situations like road traffic accidents, drones can provide aerial visuals to emergency medical services, enabling them to prepare for the severity of injuries or hazards at the scene before they arrive (O'Callaghan, 2023).

UAVs and Traffic Monitoring and Control

Addressing traffic congestion is a critical challenge because it can help reduce prolonged travel times, heightened air pollution, and adverse effects on productivity and functionality. In recent times, drones have garnered considerable attention as potential solutions. Studies have revealed that drones can play a crucial role in monitoring and managing traffic. Unlike conventional methods such as CCTVs and sensors, drones offer the advantage of providing more precise data. This is achieved by outfitting them with advanced sensors and lidar, enabling them to gather and deliver highly accurate information.

High-Speed Rail

Rail systems can help reduce congestion. For example, it was found that cities with a new rail system have, on average, seven percent less congestion and one percent less travel time than cities with no rail systems (Fageda, 2021). Numerous countries are currently incorporating high-speed rail technology into their transportation systems. Japan stands out as the pioneer, having operated its high-speed Shinkansen trains since 1964. In Europe, several nations, including Germany, France, Spain, Italy, and the United Kingdom, have adopted high-speed rail services. The networks of major high-speed rail operators in Europe are shown in Figure 19. However, China boasts the most advanced and expansive high-speed rail network globally, maintaining its status as one of the largest and fastest-growing systems worldwide (Figure 20).

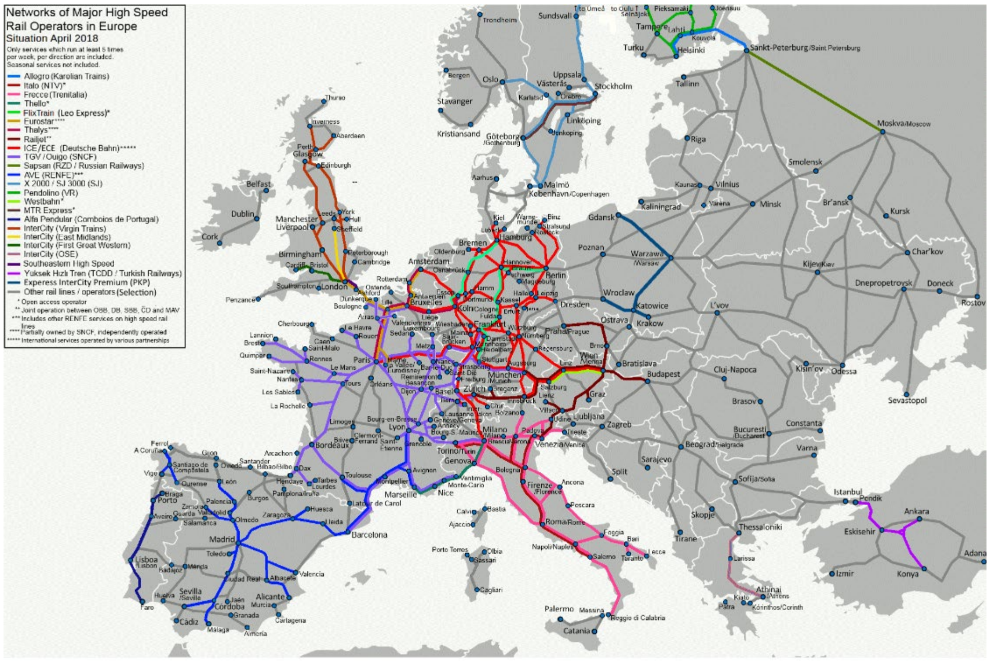


Figure 19. Networks of major high speed rail operators in Europe.

Source: (Bernese Media)

Figure 20. China's high-speed rail map.

Source: (Yaohua, 2000)

Currently, the United States does not have an operational high-speed rail system running at 220 mph.. However, plans are underway for the development of a high-speed rail project in California. According to the US High Speed Rail Association, high-speed rail (HSR) possesses significant capacity, with a single HSR line capable of transporting up to 20,000 people per hour. This is equivalent to the capacity of 10 lanes on a highway. An image showing a vision of high-speed rail in the U.S. is shown in Figure 21.

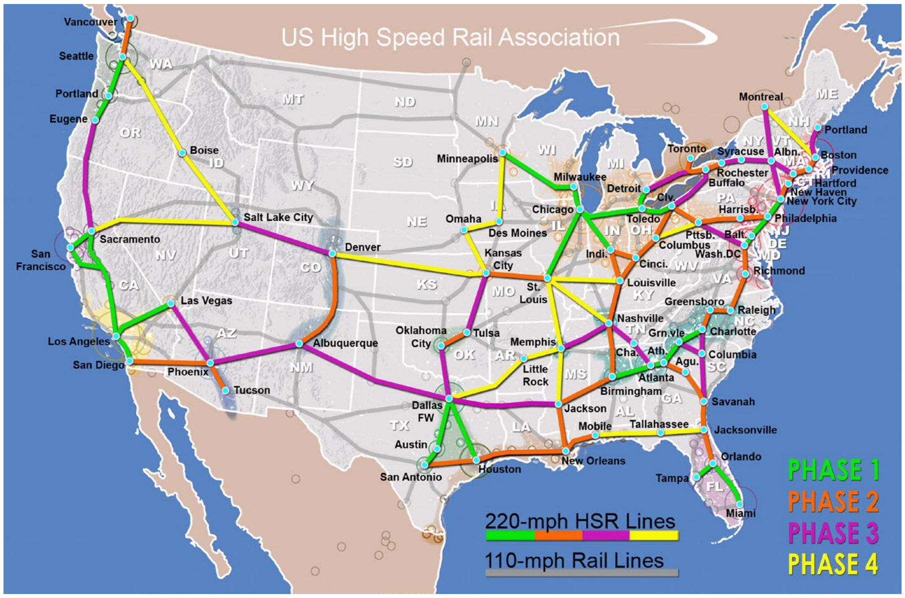


Figure 21. HSR vision map in the U.S.

Source: (US High-Speed Rail Association)

Current and Future Technologies

The technologies used in advanced transportation include AI, ML, automation, electrification, sensors, lidar, radio frequency (RF), satellite communication, cellular networks, GPS receivers, battery technology, autonomous navigation, advanced signaling and control systems, automatic train control (ATC), positive train control (PTC), and communication-based train control (CBTC) systems.

Benefits, Limitations, and Uncertainties

The benefits, limitations, and uncertainties of advanced transportation technologies, especially UAVs and high-speed rail, are provided below.

Benefits

UAVs or drones can help reduce congestion in the following ways:

- Reduce expenses related to deliveries by removing the need for drivers or trucks,
- Reduce missed deliveries,
- Reduce requirement for local transport,
- Enhance emergency service response times and safety outcomes,
- Help with traffic monitoring, and
- Provide more precise data.

One significant benefit of high-speed rail is its capacity to alleviate traffic congestion by providing an efficient alternative for medium to long-distance travel, thereby reducing the reliance on congested roadways and airports. This diversion of travelers to rail can help alleviate pressure on highways and urban road networks, particularly in densely populated regions or along major transportation corridors.

Limitations

Even though UAVs are beneficial, they also face some challenges related to the following areas.

- Safety Concerns: UAVs still face safety risks because of shared airspace with manned aircraft and populated areas. Technical failures, human error, or unexpected environmental factors can lead to accidents. UAVs can also be subject to hacking.
- Noise from UAVs causes issues.
- Regulatory Restrictions: UAV operations need to obey restrictions from aviation authorities.
- Limited Endurance: UAV batteries may not last long.
- Payload Capacity: UAVs may have limited space that can reduce options for sensors, cameras, and other equipment that can be carried.
- Weather Sensitivity: Adverse weather conditions affect UAV operations.
- Limited Range: The range of UAVs is limited by battery life, communication range, and regulatory restrictions on beyond visual line of sight (BVLOS) operations.
- Limited Autonomy: UAVs require human oversight and intervention for planning, decision-making, and emergency situations.
- Privacy Concerns: UAVs equipped with cameras and sensors can be subject to privacy concerns related to surveillance, data collection, and potential misuse of collected information.
- Costs and Maintenance: Purchasing and operating UAVs can be costly when applied in a commercial context.

High-speed rail has the following limitations:

- Limited coverage.
- Dependency on government support
- Technological obsolescence since high-speed rail technology is continually evolving, and older systems may become outdated.

Uncertainties

Several uncertainties surround the future of UAVs or drones, including:

- Regulatory Environment: Future regulations, including restrictions on operations, licensing requirements, and standards for UAV design and operation, are not evident.
- Airspace Integration: How UAVs will share airspace with manned aircraft, their communication standards, traffic management systems, and collision avoidance mechanisms are unknown.
- Public Acceptance: It is uncertain what will be public attitudes towards UAVs and how that can affect their widespread adoption.
- Technological Advancements: It is uncertain how technologies will mature and impact the UAV industry.
- Security: What will be the security measures of UAVs in the future are unknown.

- Economic Viability: Economic viability of UAVs can be affected by different things, such as market demand, competition, regulatory constraints, and technological limitations.
- Environmental Impact: Uncertainties exist related to the development of environmentally sustainable UAV technologies that can overcome things like noise pollution, habitat disruption, and others.
- Ethical and Legal Considerations: UAV face uncertainties related to privacy rights, data ownership, accountability, and liability in the event of accidents.

Uncertainties surrounding high-speed rail include:

- Future ridership levels are unknown and may change over time.
- Technological advancements bring uncertainty about the long-term importance and competitiveness of high-speed rail as a mode of transportation.
- It is uncertain how variation in market conditions and consumer preferences will disturb the demand for high-speed rail services.
- Uncertainty surrounds the reliability and safety of high-speed rail operations due to the necessity of ongoing investment in infrastructure maintenance, technology upgrades, and workforce training.

Interaction Between Area, Subareas, and Other Areas

Advanced transportation technologies could potentially interact with CAVs, TSM&O, smart and advanced signal timing and optimization, and incident management for successful deployments.

Emerging Technologies

In this section, a summary of the literature review on emerging technologies in transportation is covered. It highlights technologies in transportation that are promising but have not been fully developed, their potential effect on congestion reduction, their congestion reduction strategies, conditions, and approaches, as well as their benefits, limitations, and uncertainties.

Definition and Subareas

Emerging transportation technologies include technologies that are still in the development stages, not completely commercialized, and not extensively adopted. Similar to the advanced transportation technologies, emerging technologies use innovations that can disrupt existing transportation systems. However, these technologies may still experience technical, regulatory, and market-related challenges, and they may be in research, testing, and feasibility studies before they can be deployed at scale.

Subareas or examples of emerging transportation technologies include hyperloop, urban air mobility (eVTOL aircraft and flying cars), magnetic levitation (Maglev), underground roads, and augmented reality in navigation. Further description of each one is provided subsequently.

Hyperloop

The concept of the hyperloop was initially introduced as a novel mode of transportation in a whitepaper authored by Elon Musk in 2013. Musk envisioned a train-shaped vehicle lacking traditional wheels, designed to travel within a low-pressure or vacuum tube, operating both underground and at ground level. Elon Musk proposed that hyperloops would be most suitable for routes covering distances of less than 1500 miles, particularly highlighting routes like the one between Los Angeles and the San Francisco Bay Area. The hyperloop conceptual diagram is shown in Figure 22. The hyperloop will, ideally, run for 19 hours and use five hours for maintenance (Pérez, 2019).

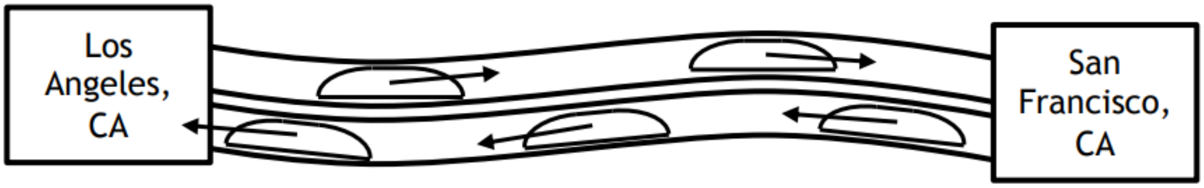


Figure 22. Hyperloop conceptual diagram.

Source: (Musk, 2013)

Urban Air Mobility (eVTOL and Flying Cars)

Urban Air Mobility (UAM) is an emerging transportation system that aims at revolutionizing urban mobility through the deployment of small eVTOL aircraft. The development of UAM is largely driven by advances in Intelligent Technology (Yang Liu, 2023). The UAM evolution trajectory begins with drones for urban logistics (see section on advanced transportation technologies), evolves to eVTOL aircraft for passenger commuting, and ultimately anticipates fully autonomous urban flying vehicles (Kai Wang, 2023).

Magnetic Levitation (Maglev Train)

The rail transportation system is among the most energy-efficient modes of transportation. One of the most modernized rail modes is Maglev, which does not exactly ride on rails. Magnetic Levitation trains, known as Maglev, can travel faster and more efficiently than conventional trains because they are able to ride on air instead of steel rails. As modern and advanced as this idea seems, this concept took off in the late 1960s, when Gordon T. Danby and James R. Powell of Brookhaven National Laboratory proposed using superconducting coils to produce the magnetic fields that would levitate the trains ("Maglev: a new approach," 2000).

Underground Roads

On May 3, 2023, Clark County in Nevada announced its approval of a new construction project by Elon Musk's company, the Boring Company. The project aims to build the "Vegas Loop," an underground transportation system that will offer fast and convenient travel to the Las Vegas community, tourists, and beyond.

Augmented Reality in Navigation

Augmented Reality (AR) is an interactive experience that combines the real world and computer-generated content (Cipresso, Giglioli, Raya, & Riva, 2018). AR can be defined as a system that incorporates three basic features: a combination of real and virtual worlds, real-time interaction, and accurate 3D registration of virtual and real objects (Wu, Lee, Chang, & Liang, 2013). In recent years, manufacturers have shown an increased interest in exploring the use cases of Augmented Reality (AR) in vehicles for various purposes. According to Fortune Business Insights, the global AR market in the automotive industry is expected to grow from 4.51 billion US dollars in 2021 to 14.4 billion US dollars by 2028.

Congestion Reduction Strategies, Conditions, and Approaches

Anticipated congestion reduction strategies and conditions of hyperloop, eVTOL, flying cars, maglev, underground roads, and augmented reality in navigation are summarized in this section.

Hyperloop

Hyperloop is projected to be an effective mobility tool in the future in many ways. Hyperloop with passenger only capsules is anticipated to have an average departure time of two minutes between capsules and a minimum of 28 passengers per capsule for 840 passengers per hour (Musk, 2013). The passenger-plus-vehicle version of the Hyperloop will depart as often as the passenger-only version but will accommodate three vehicles in addition to the passengers (Musk, 2013). The journey time on a Hyperloop system could be 10 to 15 times shorter than that of conventional rail travel (Walker, 2018). For example, a trip from Los Angeles to San Francisco in California using the hyperloop is estimated to be around 2134 seconds (35 minutes). The speed and distance of the capsule as a function of time from Los Angeles departure are shown in Figure 23 and Figure 24.

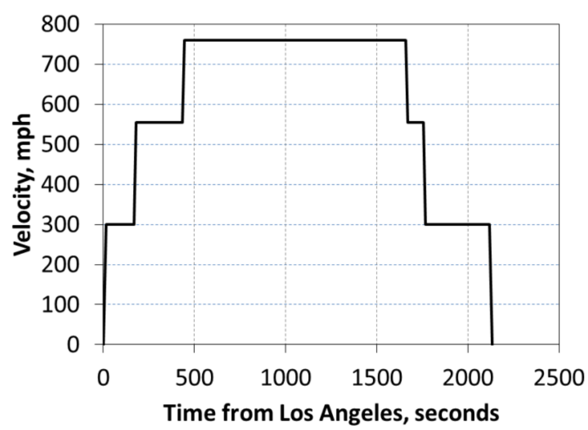


Figure 23. Speed of capsule as a function of time from Los Angeles departure.

Source: (Musk, 2013)

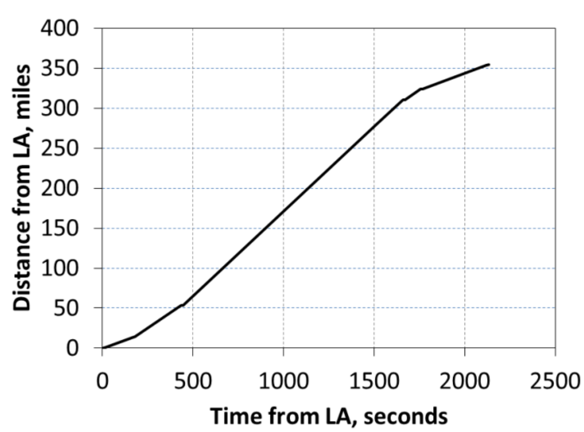


Figure 24. Distance of capsule as a function of time from Los Angeles departure.

Source: (Musk, 2013)

Moreover, hyperloop can be energy efficient with potential station-to-station travel times that are theoretically faster than other competing modes, such as flights. Hyperloop is anticipated to travel at a speed of 1,200 km/h. When tested, it has reached a speed of approximately 400 km/h. Though, the transit time of a hyperloop would be the same as air travel, which would undermine the overall speed advantage of a hyperloop, by increasing its overall journey time (Walker, 2018). Musk (2013) argued that the transit impact will be less than flights due to the higher frequency between pod departures.

Urban Air Mobility (eVTOL and Flying Cars)

An eVTOL aircraft, which can take off and land vertically, can help reduce traffic congestion in the future. Vertiports are crucial infrastructure for eVTOL, serving as the landing and docking points for the aircraft (Kai Wang, 2023).The composition of eVTOLs system is shown in Figure 25.

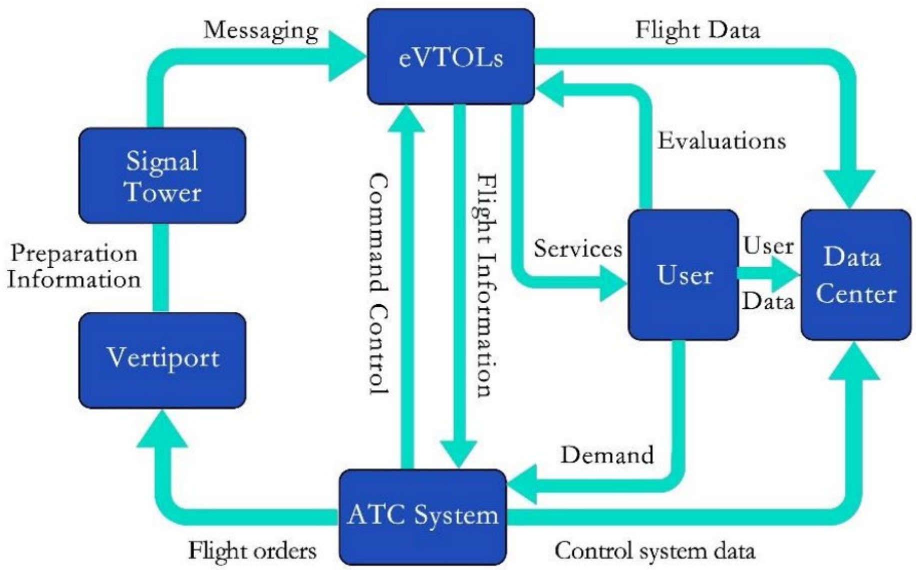


Figure 25. UAM system composition and interaction between components.

Source: (Yang Liu, 2023)

UAM or eVTOL can affect congestion in several ways. For instance, they can reduce the vehicle hours traveled (VHT), which will result in less traffic on the ground, especially during peak hours in large or very large urban areas. Rothfeld et al. found that travel time reduction is the most crucial element in the adoption of the technology. Besides, eVTOL could potentially offer more benefits in rural areas such as mountainous regions and more connectivity for islands. If demand to travel to and from an island or between multiple islands is relatively low, ferry service will be inefficient or require detours and transfers. eVTOL could become an alternative mode that provides easy access to regions with limited ground transportation infrastructure, resulting in less congestion in surrounding neighborhoods (A. Pukhova, 2021). On the other hand, UAM/eVTOL can generate more vehicle kilometers. For example, the results of a study showed that UAM can produce approximately 0.14 million more vehicle kilometers than the base scenario, an increase of 0.27 (see Figure 26). In addition, there is a possibility that the advent of this new technology could lead to increased traffic congestion in the vicinity of vertiports, as these facilities gain heightened popularity.

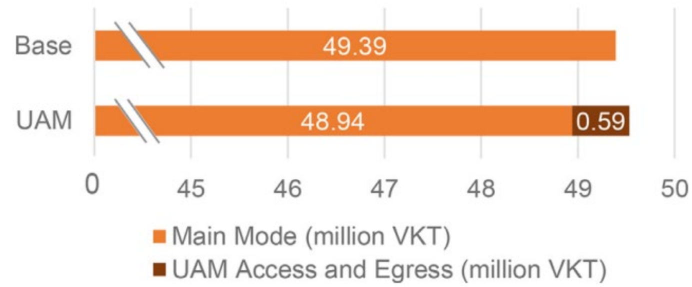


Figure 26. Comparison of vehicle kilometers traveled on the road network.

Source: (A. Pukhova, 2021)

Magnetic Levitation (Maglev Train)

The Maglev train uses a magnetic field to suspend, guide, and propel vehicles on the track (see Figure 27). It provides a sustainable and cleaner solution for train transportation by significantly reducing the energy usage and greenhouse gas emissions as compared to traditional train transportation (Qadir et al., 2021). Maglev technology can help reduce congestion. Their high speeds with minimal friction can facilitate fast trips between major cities, help reduce congestion on highways, and decrease short-haul air travel. It can also increase capacity and reduce congestion on crowded commuter routes since they can function with higher frequencies, shorter headways, and greater efficiency compared to traditional rail systems. The Maglev train can provide a connection between airports and city centers, which can alleviate congestion and enhance connectivity for air travelers. These shuttles can offer fast and convenient options in areas with congested airports and limited ground transportation infrastructure. Underground Maglev systems can enable fast and reliable transportation to reduce ground congestion in dense cities.

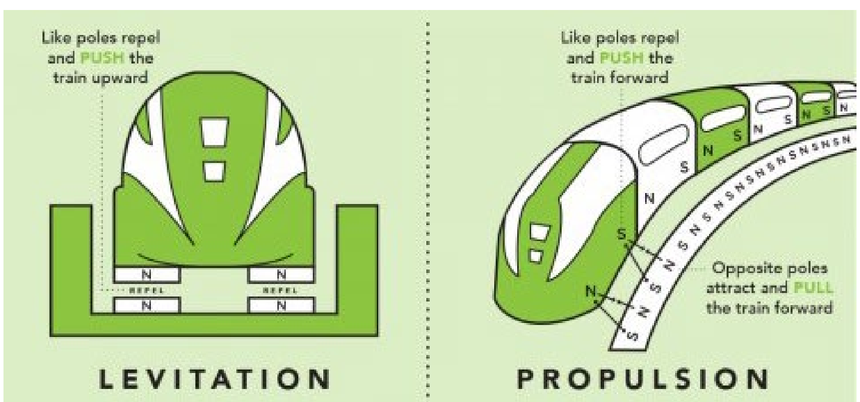


Figure 27. Magnetic levitation trains.

Source: Department of Energy

Underground Roads

Once finished, the Vegas Loop (underground road) will be able to transport over 90,000 passengers every hour, alleviating ground transportation. The city of Las Vegas and Clark County have approved a total of 68 miles of tunnel and 93 stations for the Vegas Loop. According to the Boring Company's plans, traveling in Las Vegas will be as efficient as shown in Table 4 below:

Table 4. Las Vegas Trip Distance and Travel Times

Trip	Distance	Travel Time	Fare
Harry Reid Intl Airport to Las Vegas Convention Center	4.9 Miles	5 Minutes	$10
Allegiant Stadium to Las Vegas Convention Center	3.6 Miles	4 Minutes	$6
Downtown Las Vegas to Las Vegas Convention Center	2.8 Miles	3 Minutes	$5
Downtown Las Vegas to Harry Reid Intl Airport	7.7 Miles	8 Minutes	$12

At present, the new roadway system project is only planned for Las Vegas, hence, there is limited information available about this innovative approach. However, if the pilot project manages to transport around 90,000 passengers per hour in Las Vegas, it will have a positive impact on reducing traffic congestion by decreasing VMT. The underground planned Las Vegas travel routes are shown in Figure 28.

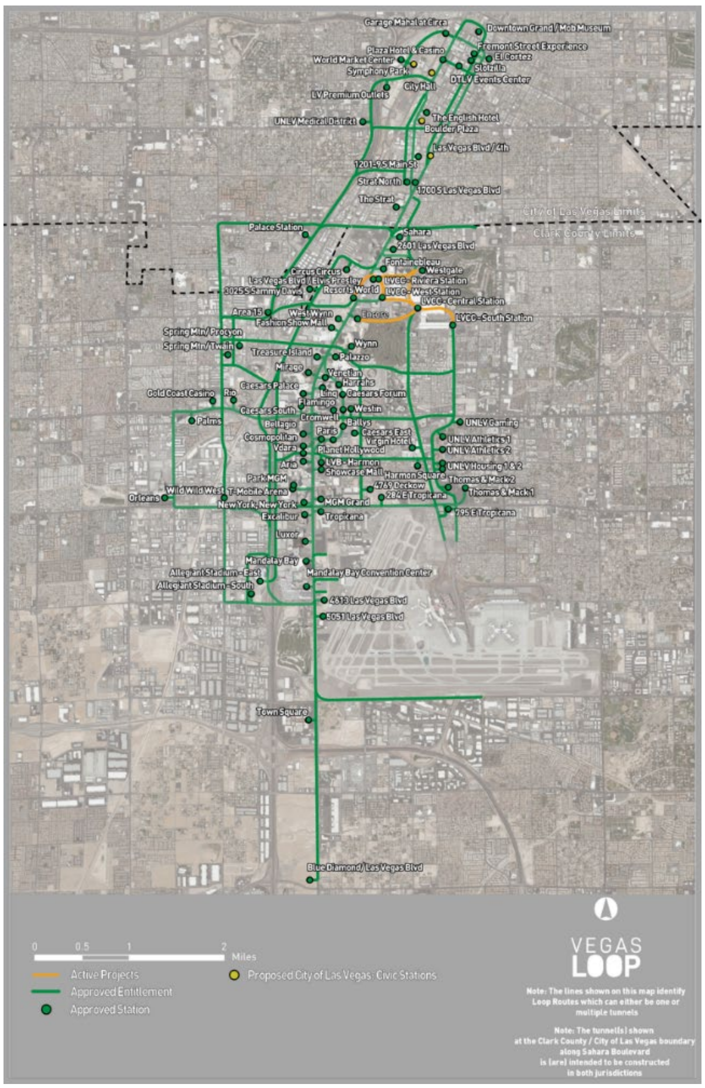


Figure 28. Las Vegas travel routes.

Source: (Company, 2023)

Augmented Reality in Navigation

There are multiple ways in which manufacturers can implement AR in their production, whether it is through an in-vehicle application or off-vehicle application. North America AR growth trends are shown in Figure 29 and an example of the use of the new navigation system is shown in Figure 30.

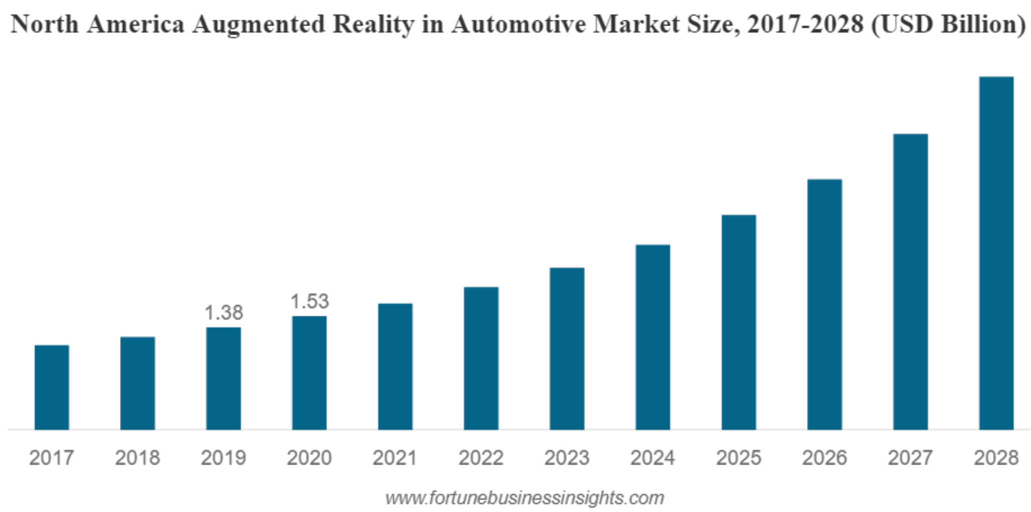


Figure 29. North America AR growth trends.

Source: Fortune Business Insights

In designing and producing the vehicle, detecting problems and maintenance needs, and sales and marketing, AR is extensively used in off-vehicle conditions. On the other hand, in-vehicle AR use cases are more focused on solutions to reduce congestion. Currently, AR is predominantly being used for enhanced navigation, Advanced Driver Assistance Systems (ADAS) visualization, and park assistance (BASEMARK, 2022).

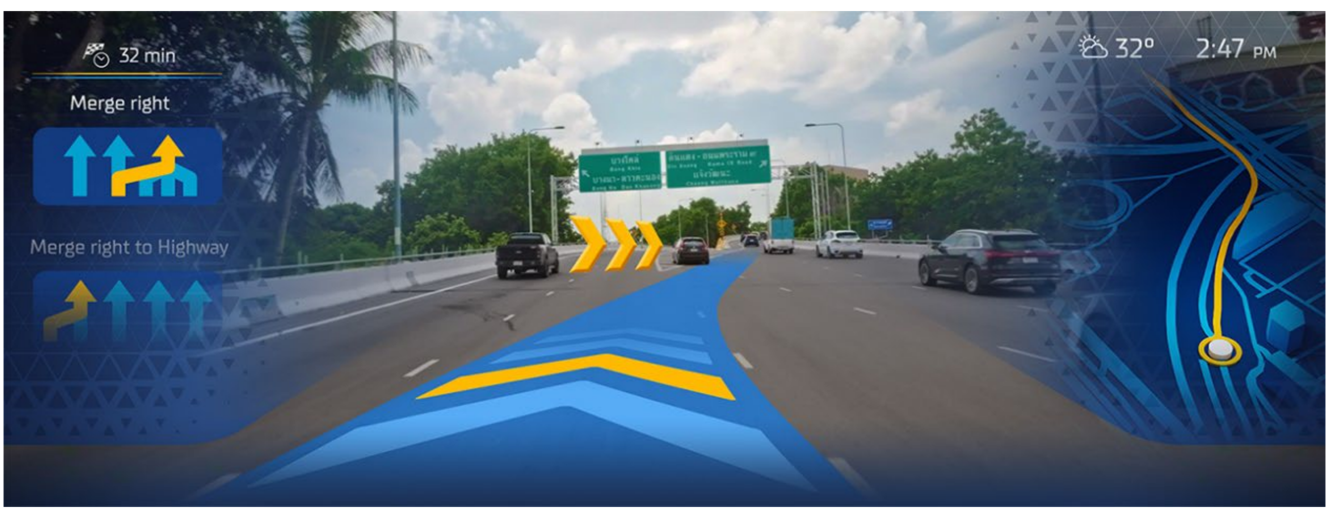


Figure 30. Example of AR use in the new navigation system.

Source: (BASEMARK, 2022)

The image illustrates AR use in vehicles via Heads Up Displays (AR HUDs), showing speed, weather, fuel, and navigation directly on the windshield. This technology enhances driver safety, parking, and object detection.

Cars like the 2022 Mercedes-Benz EQS and Audi use AR, and BMW has developed the BMW Individual 7Series Augmented Reality app to leverage these benefits. AR in traffic management can reduce congestion and improve flow with real-time data, updates, and alternative routes. This technology shows great potential for enhancing overall transportation efficiency. An example of BASEMARK 1st generation AR Enhanced Navigation is shown in Figure 31.

Figure 31. Example of BASEMARK 1st generation AR Enhanced Navigation running on public roads since 2021.

Source: (BASEMARK, 2022)

Emerging transportation technologies, though in early development stages, hold promise for reducing congestion. While some, like Maglev trains, have existed for years, only a few prototypes operate today. Significant research, development, and infrastructure investments are needed, and full implementation may take a decade or more. Governments, private companies, and researchers are collaborating globally to advance and test these technologies, which, despite limited current scientific studies, show potential for major impacts on road and railway congestion.

Current and Future Technologies

The emerging technologies use different cutting-edge technologies, including:

Hyperloop

- Maglev Propulsion
- Pods
- Sensors
- Communication networks
- Automated control algorithms to detect and respond to emergencies or system malfunctions

eVTOL

- Electric Propulsion
- Autonomous and advanced navigation systems, GPS, lidar, radar, and computer vision to detect obstacles, plan flight paths, and avoid collisions
- Vertiports

Maglev Train

- Electromagnetic Suspension

Underground Roads

- Electric Autonomous Vehicles (AEVs)
- Sensors, cameras, and onboard computers
- Electric propulsion
- Autonomous navigation systems
- Lidar and GPS
- Real-time data analytics and communication networks

Augmented Reality in Navigation

- GPS and location tracking
- Computer vision
- Sensor fusion
- Spatial mapping and localization
- Augmented reality displays
- Gesture recognition and interaction
- Cloud-based services
- ML and AI

Benefits, Limitations, and Uncertainties

Benefits

Emerging technologies have several benefits. They can enable travel at high speeds, which can decrease travel times between locations and enable fast long-distance trips. They can reduce congestion on highways, railways, and airports by providing an alternative mode of transportation. Many of them can carry large numbers of passengers (sometimes thousands of passengers per hour) and freight, including hyperloop, Maglev trains, and underground roads, in a short amount of time because of their speeds and frequent services. This can help relieve congestion on busy roadways. They can effectively provide connections between cities and regions and decrease the need for long-distance commuting and inter-city travel by car or plane.

The emerging transportation can add to transportation options, offer alternative transportation alternatives to private vehicles, and assist in decreasing traffic congestion on highways and at airports. Some of them can help reduce ground congestion, like eVTOL or flying cars. A few emerging technologies, including AR in navigation, can assist with dynamic route guidance and safety. For example, the hands-free Interaction provided by AR navigation can minimize distractions and cognitive load, and help drivers stay focused on driving while receiving essential navigation information, reducing the risk of accidents and traffic congestion. AR navigation systems can use crowdsourced traffic data from connected vehicles, smartphones, and other sources to provide real-time updates about traffic conditions, road hazards, and incidents. Those updates can be used by travelers to select alternate routes and avoid congestion hotspots, reducing overall traffic congestion and improving traffic flow. The technologies, such as eVTOLs, do not necessitate vast infrastructure for their operation. They can also help with remote places access and facilitate travel to rural areas.

Limitations

Emerging transportation technologies are in experimental stages and face technical challenges impacting reliability, efficiency, and safety. Effectiveness is limited by the lack of real-time data, connectivity, and route coverage. Technologies like AR in navigation also face privacy and security concerns over data collection and sharing. Additionally, limited user awareness and training can restrict adoption, reducing their potential to alleviate traffic congestion.

The regulatory approval process for certifying emerging transportation technologies can limit their adoption, requiring significant time and resources. Without proper regulations, these technologies may lead to increased trips and congestion. Additionally, high costs may make them unaffordable for some passengers, limiting their demand and congestion reduction benefits.

Public skepticism about the safety, reliability, and feasibility of emerging transportation technologies can hinder their adoption. Building trust and demonstrating benefits are crucial for public acceptance and reducing congestion. For instance, despite decades of testing, Maglev trains have faced accidents, such as the 2006 crash in Germany that resulted in 23 deaths and 10 injuries (News, 2006). Although fatalities are not substantial, public wariness persists, and Maglev must prove its reliability to gain acceptance. Besides safety concerns, high costs are a major issue for new technology. The Washington-Baltimore Maglev line is estimated to cost $10-12 billion for 40 miles. Until September 2023, the Incheon Airport Maglev, one of the few operational, transported only 4,000 passengers daily, about 11% of expected levels.

Emerging technologies may increase demand and contribute to congestion, with benefits varying by area. For example, Pukhova et al. found eVTOLs have limited potential to improve urban travel due to their small capacity and lengthy boarding, takeoff, and recharging times. eVTOLs would only significantly reduce travel times for certain routes, like between remote areas with limited transport infrastructure.

Uncertainties

Uncertainties surround emerging technologies, including their maturity, scalability, reliability, and safety. These doubts affect their potential to reduce congestion. Additionally, uncertainties exist about regulatory approval, safety standards, operational requirements, market demand, and mode choice preferences. The readiness of these technologies for large-scale deployment and reliable, efficient operation is unknown. Public preferences, attitudes, and behaviors towards these technologies are unclear, and concrete data on their impact on transportation infrastructure and incidents is currently unavailable. As mentioned previously, certain researchers have delineated specific areas including noise, safety, visual pollution, and privacy, that may raise potential concerns for prospective customers in the future (Adam P. Cohen, 2021).

Interaction Between Area, Subareas, and Other Areas

Emerging technologies involve shared transport, incident management, multimodal transportation, and smart navigation systems. To mitigate congestion, these technologies necessitate ancillary transport modes like biking, e-scooters, and carpools for vertiport or station access. Incident management and smart navigation streamline routes and incident resolution, alleviating congestion near stations.

Chapter 3. Expert Interviews

Leveraging the expertise of professionals across congestion mitigation domains is invaluable for crafting a comprehensive roadmap to address the needs of diverse stakeholders. Our project team conducted interviews with experts, ranging from government agency engineers and managers to consultants and researchers, via teleconferences. The CUTR team coordinated these sessions, facilitating and documenting discussions. The insights gathered were then synthesized to create succinct summaries for each congestion reduction area.

Smart and Advanced Signal Timing and Optimization Systems

Smart and advanced signal timing and optimization experts were interviewed to inquire how the systems can address congestion issues. Four different experts working for a city, consulting firm, metropolitan area, and university participated in the interviews. The interviews are summarized below.

Definition and Subareas

Smart and advanced signal timing and optimization systems refer to utilizing technologies to adapt signal timings according to varying traffic conditions. Signal timing is addressed differently for recurring and non-recurring congestion scenarios. Recurring congestion, typically caused by bottleneck or capacity issues, necessitates operational changes such as signal timing adjustments. Engineers focus on ensuring appropriate traffic signal coordination, phase splits, and green time allocation between movements. Non-recurring congestion, stemming from incidents or breakdowns, presents unique challenges, particularly in ensuring timely response and implementation of special timing plans to address the congestion caused by the incidents.

Congestion Reduction Strategies, Conditions, and Approaches

The various smart and advanced signal timing and optimization strategies and approaches that can be used to mitigate traffic congestion include the following:

- Engineers can emphasize real-time adaptive strategies like adaptive signals, traffic-responsive timing plans, and vehicle-signal communication. Adaptive signals offer optimized timing plans, particularly during off-peak periods. However, solutions face limitations once volume-to-capacity thresholds are reached.
- Engineers can implement incident signal timing plans on arterial detour routes during freeway incidents to mitigate non-recurring congestion. By proactively implementing and adjusting special incident timing plans through a traffic management center upon incident detection, more green time can be allocated to diversion routes, minimizing congestion and its duration.
- Engineers can use Automated Traffic Signal Performance Measures (ATSPM) to better understand traffic conditions for all approaches.
- A cloud-based transit signal priority system facilitates automatic vehicle location for transit vehicles. However, it is important to consider factors like the level of congestion due to bus signal priority. While it may alleviate bus traffic, it could also potentially exacerbate congestion for other vehicles. Thus, a holistic assessment is necessary to gauge its overall impact on traffic flow and transit efficiency.

- Utilizing signal timings to regulate traffic speed can effectively lower the occurrence of crashes and alleviate non-recurring congestion, particularly benefiting pedestrians and bicyclists.
- Computer-aided dispatch system for transit and emergency vehicles for preemption and saving lives. The related software and more modern systems need a better network and a better strategy to address congestion.

Current and Future Technologies

The current and future technologies highlighted by the smart and advanced signal experts are highlighted next.

Current Technologies

- Adaptive technologies have existed for a while and can help address recurring and non-recurring congestion. However, continuous improvement and advancement are important for improving the performance of the systems.
- Advanced traffic controllers (ATCs) and ATSPM are also currently being used and are expected to be the next wave of adaptive control technologies.
- Cloud-based transit signal priority system is currently being used and can help track transit vehicles.
- Sensors, peer-to-peer data sharing, and other Bluetooth technologies are being explored for signal timing and optimization.

Future Technologies

- In the future, ATSPM, big data, and probe vehicle data will be used to dynamically adjust signal timing based on commuters' trip history, and optimize traffic flow. Expected within 10 years, this technology will utilize arrivals on red and green to adjust signal offsets in real time, marking a significant advancement in signalized intersections.
- A revolutionary shift in signal control tech is not expected for 10-20 years. Beyond that, changes are uncertain. Utilizing connected or autonomous vehicles to predict routes and traffic density could inform adaptive signal timing plans, enhancing future traffic management.
- Technology is expected to evolve and address some of the highlighted challenges in the limitations section. As cars get smarter, intersections get smarter too.
- Advanced traffic signal strategies will revolutionize information sources. Currently, traffic signals operate as closed systems, relying solely on internal sensors. However, with connected and autonomous vehicles, signals will communicate beyond their immediate vicinity, enhancing coordination, especially in urban environments.

Benefits, Limitations, and Uncertainties

Benefits

- By dynamically adjusting signal timings based on real-time traffic conditions, the systems optimize traffic flow, minimize delays, and enhance overall transportation efficiency.
- The systems can prioritize high-volume routes, improve intersection operations, and facilitate smoother traffic flow throughout urban areas, effectively reducing congestion and improving travel times for commuters.

- Adaptive signals are more beneficial for non-recurring congestion or for changing traffic conditions around a shopping mall or a road to the beach, or due to weather.
- Transit signal priorities to support a good transit system are beneficial for reducing congestion.

Limitations

- A shortage of manpower and resources presents challenges in implementing new technologies, as insufficient staff may struggle to keep pace with evolving technology and maintenance demands.
- One obstacle in implementing smart and advanced signal timing and optimization systems is the need for experienced and trained operation and maintenance teams familiar with the new technologies.
- Education and workforce development are crucial, requiring more hands-on training with real-world case studies to adequately prepare individuals for the demands of the field.
- Adapting to shifts in people's behavior and choices poses another challenge when utilizing new signal systems and technologies to alleviate traffic congestion.
- Institutional barriers could impede future advancements in smart signal timing technologies. Overcoming these obstacles may require adjustments or changes to the existing institutional structure, emphasizing the importance of interoperability.

Uncertainties

Some uncertainties exist in the smart and advanced signal timing and optimization systems as highlighted next.

- Uncertainty surrounds the readiness of both infrastructure and people for implementing smart signal systems. Local agency capabilities vary widely, with many remote counties and small cities lacking the expertise, workforce, and funding needed to adopt these new technologies.
- While technology will undoubtedly assist, its future impact remains uncertain. Advancements will likely yield more data, enhancing the reliability of performance measures. These measures will offer insights into system efficiency and effectiveness, shaping our understanding and utilization of future systems.

Looking into the Future and Percent Congestion Reduction

In the future, expanding lanes is not viable. Smart signal timing will continue to mitigate traffic congestion but will not solve congestion problems entirely. Current systems offer around three percent congestion reduction, while future smart technology may achieve 5-10 percent. To achieve a 15 percent reduction, proper implementation and placement are crucial. In the short term, no major changes are expected, but in the midterm (10-20 years), adaptive systems may evolve. Beyond 20 years, changes are uncertain.

Overall, some of the changes that may happen in the future include:

- In the future, intersections may have distinct signal timing regimes for various modes like bicycles, pedestrians, trams, and cars, all operating concurrently but separately within a unified signal system, reflecting diverse transportation needs.
- In the future, priorities and preemption systems will be established for trucks, including commercial trucks. Diverse priority regimes based on roadway types or uses will emerge. For instance, collector streets may prioritize private vehicles and bicycles, while highways near ports will prioritize trucks, all interconnected for seamless operation.
- ATSPM will be used to measure multimodal transportation performance (e.g., transit, bike, and pedestrian delays).

Interaction Between Area, Subareas, and Other Areas

Smart and advanced signal timing and optimization systems are interconnected with various aspects of transportation for traffic congestion reduction, including CAVs, public transportation networks, TSM&O, incident management protocols, multimodal transportation initiatives, and advanced and future transportation technologies.

Traffic Incident Management

Interviews were conducted with four experts specializing in the field of incident management. These professionals work for private companies assisting state and local transportation agencies with traffic incident management. A synthesis of these interviews is presented below.

Definitions and Subareas

Definition

TIM uses available resources and established procedures to respond to incidents related to crashes, weather, special events, or others, to minimize the time people are exposed to the incidents and maximize traffic throughput as quickly and safely as possible. It involves multiple agencies with established protocols detailing each member's role. Collaborating agencies ensure clear communication and coordinated efforts, prioritizing safety and efficiency based on predefined procedures and objectives. TIM emphasizes proactive planning and cohesive teamwork to achieve effective incident management outcomes.

Subareas

There are a few perspectives on TIM’s subareas. The first perspective involves all the teams participating in incident management, including Law Enforcement (LE) Agencies, Emergency Medical Services (EMS), Fire Departments, Transportation Agencies, Towing and Recovery Services, Emergency Management Agencies, and Communication Centers. Another viewpoint involves breaking down subareas into policy, protocols, procedures, signs and markings, special events, work zones, ITS, road rangers, natural disasters, technology, response protocols, and training.

Congestion Reduction Strategies, Conditions, and Approaches

TIM is vital for addressing congestion when operating at peak efficiency. It functions as an integrated system, necessitating seamless teamwork among multiple agencies. Effective strategies include promptly detecting, responding and clearing incidents, providing alternate routes, and optimizing traffic flow. Adherence to established procedures is crucial for peak performance, as delays in incident clearance may occur if any team encounters response issues.

The conditions for optimal performance comprise:

- Adequate resources for incident scene clearance.
- Understanding of established procedures and responsibilities by all team members.
- Implementation of a robust communication strategy.
- Efficient coordination and collaboration among all involved agencies and personnel.

- Regular training and drills to maintain proficiency and readiness.
- Utilization of technology and real-time data for effective decision-making.
- Quick response and deployment of resources to minimize incident duration.
- Continuous evaluation and improvement of incident management protocols based on lessons learned.

Incident Management plays a critical role in addressing both recurring and non-recurring congestion. During the planning phase, a thorough analysis of various incidents informs the development of comprehensive policies and procedures. When incidents occur, specific aspects of the process are applied based on congestion management needs, ensuring timely and effective response. The key to successful traffic incident management is communication, coordination, and collaboration among all incident responders.

Current and Future Technologies

Current Technologies

- Detection technologies encompass various methods such as cameras, aerial surveillance via drones or aircraft, news media monitoring, WAZE, speed measuring devices, and various types of volume measuring devices.
- Vehicle equipment includes units that transmit data to platforms like Waze or Google Maps, alerting drivers to seek alternative routes in response to incidents.
- Information devices include dynamic message signs, portable message signs, and other message signs.

Future Technologies

- **Short-term:** Drones offer promising potential for congestion management, benefiting from reduced costs, enhanced user-friendliness, and evolving legal frameworks. Additionally, data-driven analysis plays a crucial role in predicting incident locations, aiding proactive incident management strategies.
- **Medium-term:** The emphasis shifts to robust data platforms that integrate self-driving technologies and essential instrumentation for effective incident management. Machine learning (ML) and artificial intelligence (AI) algorithms are pivotal in predictive use cases, particularly within the roadway sector.
- **Long-term:** As connectivity and automation rise, vehicles will communicate with Traffic Management Centers (TMC), facilitating proactive signals instructing cars to slow near potential crash sites. With increasing data from the automotive fleet, AI becomes vital for swift, safe responses, reducing delays. These expectations align with generational shifts, emphasizing rapid, data-driven decision-making, especially among Gen Z and Gen Alpha.

Benefits, Limitations, and Uncertainties

Benefits

Successful incident management is pivotal for ensuring the safety of both responders and motorists and significantly reducing vehicle delays and non-recurring traffic congestion caused by the incident. Effective incident response prevents chaotic scenarios where individuals may resort to risky behaviors, such as driving against traffic flow or off-road, to bypass congestion. Additionally, timely incident clearance reduces secondary incidents, such as rear-end collisions or rubbernecking, thereby alleviating traffic congestion and enhancing overall roadway safety.

Limitations

While TIM can mitigate congestion, limitations exist. Resource availability, notably the number of freeway patrols (e.g., Florida road rangers), poses challenges. First responder cooperation is vital but varies by location, sometimes hindered by communication issues like radio channel congestion.

Uncertainties

An uncertainty lies in the high turnover of first responders, which is likely driven by the significant stress associated with the job. The demanding nature of first response work, which often involves exposure to traumatic incidents, long and irregular hours, and high physical and emotional demands, contributes to burnout and job dissatisfaction. This high turnover rate presents a major challenge for maintaining a stable and experienced workforce.

Looking into the Future and Percent Congestion Reduction

The impact of TIM on reducing congestion depends on the location and existing strategies. The effectiveness of TIM in mitigating traffic congestion varies and is influenced by whether the TIM system is newly implemented or already well established. Newly implemented TIM systems may result in modest congestion reduction. Mature TIM systems can lead to significant reductions in congestion. Based on the experts' opinions, the effectiveness of congestion reduction through TIM systems varies widely, ranging from 25 percent to 75 percent, depending on the system's maturity. Future improvements could prioritize incident prevention, leading to faster responses to more severe incidents.

Interactions Between Area, Subareas, and Other Areas

TIM seamlessly integrating with Smart and Advanced Signal Timing and Optimization Systems, Smart Navigation Systems, and TSM&O initiatives can significantly reduce traffic congestion. As CAVs advance, they hold great potential for facilitating efficient data communication between traffic management centers and enhancing the overall coordination and effectiveness of traffic management strategies.

Transportation Systems Management and Operations (TSM&O) Strategies

Four experts in TSM&O were interviewed to understand how TSM&O can help reduce congestion. The experts came from different backgrounds, including the Department of Transportation, Metropolitan Planning Organization, and Transportation Institute. A summary of all four interviews is presented next.

Definition and Subareas

Definition

The American Association of State Highway and Transportation Officials (AASHTO) defines TSM&O as "a set of strategies to anticipate and manage traffic congestion and minimize the other unpredictable causes of service disruption and delay, thereby maintaining roadway capacity while improving reliability and safety." TSM&O focuses on optimizing the management and operation of the current transportation infrastructure to maximize return on investment through advanced technologies and coordinated programs. A significant portion of the transportation network operates below its maximum capacity for much of the day, experiencing congestion mostly during peak periods such as rush hours. For instance, freeways often see heavy traffic only during these peak times and remain relatively free flowing during off-peak hours. This pattern suggests that rather than continually expanding infrastructure, transportation professionals can apply TSM&O strategies to better manage and mitigate congestion during these critical periods. By doing so, they can improve traffic flow and system reliability, thus reducing the long-term need for costly expansion projects.

TSM&O Subareas

The subareas of TSM&O include:

- Traffic signal retiming and traffic signal system maintenance
- Automatic traffic signal performance measures (ATSPM)
- Active arterial management (AAM)
- Integrated corridor management (ICM)
- Event or traffic incident management
- Work zone
- Traveler information
- Freight management
- Integrated corridor management
- Managed lanes
- Parking management
- Congestion pricing
- Transit signal priority
- Connected and Automated Vehicles (CAV) Systems
- Intelligent Transportation Systems (ITS) Communications
- Freeway Management Systems (FMS)
- Wrong-Way Driving Detection and Warning (WWD)
- Regional and Statewide ITS Architectures
- Decision support systems (DSS)
- Emergency vehicle preemption (EVP)

TSM&O can also be subdivided by facility or by approach. It can be divided into arterials versus freeways, active demand management, active parking management, active traffic management, which address traffic before, during, and after it gets on the network and then also once it leaves the network.

Another way to subdivide TSM&O is as follows:

- Technology widgets, such as signal systems, emergency services that get preempted signals, ramp metering, etc.
- Non-technology widgets, such as access management, raised curb, right turn bays, and left turn bays.
- Incident management uses technology to detect and respond in a systemic way (corridor based), such as traveler information.
- Area wide programs, such as ride sharing, encouraging multimodal transportation (informational type campaign), park and ride, etc.

TSM&O may depend on the need of the agency or operator. If the operator is a municipality, then surface streets are going to be their focus. Thus, their sub-areas are strategies dealing with surface streets. If the operator is a state DOT or a TMC, they deal primarily with the freeway network and those are their subareas, including toll facilities or managed lanes facilities. Where the two intersect include ICM, an arterial network that is operated by the city, and others. In addition, in case of an incident on the freeway, traffic is often diverted onto a surface or arterial street.

Congestion Reduction Strategies, Conditions, and Approaches

TSM&O strategies can help address both recurring and non-recurring congestion. The various TSM&O strategies and approaches that can be used to help with congestion include the following:

- TSM&O strategies can utilize existing roadway capacity to mitigate recurring congestion.
- Top arterial TSM&O strategies include effective traffic signal timing, traffic signal maintenance, AAM, ATSPM, EVP and ICM.
- TSM&O strategies can support traffic incident management to mitigate non-recurring congestion. They can be applied to manage incidents, special events, and work zones within the networks.
- Transit signal priority can help promote transit to mitigate traffic congestion issues.
- Work zones could cause lane restrictions and congestion. Providing alternate route information, closures, and dynamic queue warnings helps drivers avoid unfamiliar situations and reduces crash risks.
- TSM&O includes multimodal tactics, transit, tolling, event management, and foundational elements like performance measurement, monitoring, and traveler information to ensure system effectiveness.
- TSM&O is data-driven, prioritizing areas with traffic congestion or high crash rates affecting mobility, safety, or both. Metrics like travel-time indices, crash frequency, and severity, help identify priority corridors for TSM&O strategy implementations.
- Alleviating congestion involves deploying traveler information, providing travel options, implementing traffic management strategies, and collaborating on offsite shuttles and parking.

Recurring delays and non-recurring delays are not separate because by eliminating non-recurring delays that constantly happen at a location, the agency can eliminate the recurring delays. Similarly, the existence of recurring delays provides opportunities for non-recurring delays to happen. Thus, the two challenges overlap.

Current and Future Technologies

Current Technologies

The main technologies that are deployed when implementing TSM&O strategies include:

- Traffic management center (TMC) technology that integrates real-time data, communication systems, and control tools to monitor and optimize traffic flow, enhance safety, and manage incidents effectively.
- Sensor technologies that can provide third-party (e.g., INRIX, Waze, and Here) data or real-time information (GPS pro vehicle data used in traveler information).
- Central signal management software to manage and monitor traffic signal systems.
- Fiber optic communication networks.
- Traffic monitoring cameras.
- Dynamic message signs.
- Non-intrusive vehicle detectors.
- TSP and EVP-related technologies.
- CAV Roadside Units (RSU) to broadcast signal phasing and timing (SPaT) and basic safety messages (BSM).

Future Technologies

In the future, transportation agencies will increasingly rely on their own data or third-party data, transitioning from traditional pavement sensors to Bluetooth technology for more reliable and affordable data collection. Additionally, data from connected and autonomous vehicles (CAVs) will play a significant role, feeding into a centralized data exchange for network operation and issue identification. Over the next decade, CAV advancements, including electric and autonomous vehicles, as well as advancements in AI and edge computing, will become more impactful. Smart work zone (SWZ) technologies and real-time data analytics systems will also see growth, with anticipated enhancements from AI in the coming years.

Benefits, Limitations, and Uncertainties

Benefits

The benefits of TSM&O strategies can be summarized as:

- TSM&O strategies can effectively reduce recurring and non-recurring traffic congestion.
- TSM&O strategies are low-cost alternatives and can be deployed quickly when compared to adding lanes, which can take multiple years.
- TSM&O techniques yield big returns on value or investment, such as traffic signal retiming, leading to substantial returns.
- TSM&O strategies provide valuable information and enable agencies to effectively reduce congestion and mitigate the occurrence of both primary and secondary crashes.
- TSM&O strategies, like managed lanes such as toll roads, enhance travel time reliability by reducing delays, reflecting people's preference for dependable trips over speed.
- Increased collaboration and cooperation between states and local agencies have resulted from TSM&O planning, implementation, and operations.
- TSM&O techniques enable the development of real-time data analytics and reporting systems, dashboards, and other tools for proactive assessment of transportation performance.
- TSM&O strategies help with inclusivity and equity.
- TSM&O can help improve sustainability and reduce greenhouse gas emissions.

Limitations

In the U.S., the primary challenge in TSM&O is its reactive nature; transitioning to a proactive approach requires robust data, advanced algorithms, and machine learning systems to predict congestion onset and implement preemptive measures. Countries like the Netherlands and Germany have already achieved this, utilizing sophisticated algorithms and Traffic Management Centers (TMCs) to forecast congestion and take preemptive actions, such as implementing variable speed limits to stabilize traffic. Ultimately, the goal is to avoid congestion altogether or minimize its duration, rendering costly road expansions unnecessary for brief peak periods. Additionally, alongside operational improvements, other measures can further enhance traffic flow efficiency.

Uncertainties

Uncertainties persist in TSM&O implementation, notably in their impact on travel behavior and improving pedestrian and bicycle safety, often overshadowed by vehicular traffic focus. Resource allocation challenges arise for ongoing operations and maintenance of TSM&O technologies, including ensuring the presence and training of traffic personnel in RTMCs. Disputes over national standards delay CAV communication system deployment, while collecting and analyzing vehicle telematics data for mobility and safety concerns pose cost-effectiveness challenges.

Looking into the Future and Percent Congestion Reduction

Future direction for TSM&O strategy implementations is not easy to predict, but increasing communication bandwidth and data analysis capacity will facilitate faster data collection and analysis for improving and monitoring traffic flow in the future. Additionally, as electrification of transportation expands, challenges such as charging infrastructure and operational costs must be addressed. TSM&O has the potential to significantly reduce traffic congestion by making the most use of existing capacities, with outcomes varying based on factors like resource allocation. It is viewed as a more beneficial approach than widening roadways but requires cultural shifts and consistent budget allocation.

In the future, vehicle GPS data will play a crucial role, enhancing real-time traffic information for planning and resiliency efforts. Over the next 5-10 years, data will drive traffic management improvements, influenced by factors like remote work trends. In the future, traffic signals may respond to vehicle presence via CV technologies without pavement loops, and cloud-based data will enhance traffic management strategies. Integrated corridor management presents opportunities for congestion reduction by directing motorists to less crowded routes. TSM&O's impact on congestion reduction is expected to be significant on interstate and turnpike roadways, as well as major urban arterial corridors, which are crucial for freight traffic and coastal evacuation due to hurricanes.

Based on the experts' opinions, TSM&O can help reduce traffic congestion by 60 percent on the high end and 30 percent on the low end since TSM&O covers a variety of strategies and innovative technologies. The percentage will depend on several factors, such as the availability of resources, knowledge, and experience of staff, strategies implemented, and technologies adopted.

Interaction Between Area, Subareas, and Other Areas

TSM&O acts as a crucial framework encompassing many key areas for congestion mitigation, including Smart and Advanced Signal Timing and Optimization Systems, Multimodal Transportation, Public Transportation Systems, Incident Management, CAVs, and other areas using technologies. The relationship between TSM&O strategies and emerging technologies like CAVs is expected to evolve within five years, while advancements in public transportation systems will progress over the next 5-10 years.

Multimodal Transportation

Definitions and Subareas

Definition

Multimodal transportation is the integration of transportation and land use that supports modal diversity to meet the needs of all system users. Multimodal transportation allows users to use various transportation modes, increasing mobility and accessibility for the movement of people and goods in a safe and efficient transportation system. Also, it is the network that offers redundancy of the transportation mode, meaning that you have different modes overlaying the entire city, and people have the choice to take the one they want, but also on the city and more regional context.

Subareas

Multimodal transportation includes land use development, surface transportation, personal vehicles, freight, and bicycles-basically any type of mode that can move people from one place to another.

Congestion Reduction Strategies, Conditions, and Approaches

Multimodal transportation is a versatile and effective strategy for mitigating congestion, but its success depends on factors such as supportive policies, public awareness, well-planned development, and a well-integrated transportation network. By addressing these conditions, multimodal transportation can play a pivotal role in creating more sustainable and efficient transportation systems.

Multimodal transportation plays a crucial role in alleviating congestion by distributing demand across various modes of transportation and dispersing traffic across different routes and paths. By offering commuters a range of travel options, such as public transit, biking, walking, carpooling, and ride-sharing, multimodal transportation reduces reliance on single-occupancy vehicles and helps optimize the use of existing infrastructure.

Key conditions for the successful implementation of multimodal transportation include robust policy frameworks and public education initiatives. Educating the public about the benefits of different transportation modes and how to utilize them effectively is essential for encouraging mode shifts and reducing congestion. Additionally, well-planned land use and development strategies are critical to ensure that destinations are accessible within reasonable timeframes and distances, thereby promoting the use of alternative modes of transportation.

A fully developed multimodal transportation system requires a well-designed, connected, and comprehensive network that seamlessly integrates various modes of transportation. This network should provide convenient and efficient connections between different modes and offer reliable and accessible transportation options for all users.

Multimodal transportation is effective for addressing both recurrent and non-recurrent congestion. By offering diverse travel choices and flexible routing options, multimodal systems can accommodate fluctuations in demand and adapt to changing traffic conditions, helping to manage congestion in both everyday commuting scenarios and during special events or incidents.

Current and Future Technologies

Current Technologies

In the short term, signal optimization and upgrading detection equipment on tracks will enhance transportation efficiency. Another example is performance-based parking, which enables users to find available parking spots, costs, and alternative options through apps or websites, reducing time spent circling for parking.

In the medium term, we can expect to see advancements in drone delivery, while MaaS will become more prevalent in the long term, transforming how people move within cities.

Other technologies include GIS and big data analytics, which track movement patterns and help planners optimize transportation networks. Connected vehicle technologies prioritize modes like transit, biking, and walking, improving efficiency and safety.

Future Technologies

Future technologies in multimodal transportation are focused on seamlessly integrating different modes of transportation to enhance mobility, accessibility, and safety. Looking ahead, emerging technologies like drone delivery and Mobility as a Service (MaaS) will revolutionize transportation. Drone delivery promises to streamline package delivery, while MaaS integrates various transportation services into a single platform, offering seamless door-to-door mobility options.

Benefits, Limitations, and Uncertainties

Benefits

Well-developed multimodal transportation systems contribute to increased resilience in urban areas. Unlike auto-oriented systems, where disruptions to one mode of transportation can lead to widespread congestion and gridlock, multimodal systems offer alternative routes and modes of travel. This redundancy helps to distribute traffic more evenly across various modes, minimizing the impact of disruptions and incidents on overall mobility. Additionally, multimodal transportation encourages mode shifting, allowing individuals to choose the most efficient and appropriate mode for their trip, thereby reducing congestion on any single mode or route. Overall, the presence of multiple transportation options enhances the city's ability to withstand and recover from disruptions, ensuring smoother mobility even during unforeseen events.

Limitations

Limitations exist in the accessibility of multimodal transportation, as only individuals with appropriate apps on their phones or credit cards linked to systems can utilize e-bikes, e-scooters, shared cars, and rideshare services. Additionally, concerns about privacy may deter some individuals from using these services. Another limitation is the challenge of promoting the adoption of multimodal transportation, as some people may resist change and prefer traditional modes of transportation.

Uncertainties

Uncertainties in developing multimodal transportation to reduce congestion stem from various factors, including limited funding and the substantial costs required for its development. Securing adequate funding presents a significant challenge, as building multimodal transportation systems entails substantial investments in infrastructure, technology, and operations. These costs include the construction of transit facilities, the implementation of new technologies, and the maintenance of existing transportation infrastructure. Additionally, uncertainties arise from the complexity of coordinating different modes of transportation and integrating them into existing transportation networks. This requires careful planning, collaboration among stakeholders, and overcoming regulatory and logistical challenges. Overall, addressing these uncertainties requires strategic planning, innovative financing mechanisms, and effective governance structures to ensure the successful development of multimodal transportation systems.

Looking into the Future and Percent Congestion Reduction

In an optimally designed and planned multimodal transportation system, congestion could theoretically be minimized to zero percent. Even in densely populated urban areas with high levels of activity, efficient multimodal networks would allow for smooth traffic flow and minimal congestion. This would be achieved through strategic placement of transportation hubs, well-coordinated schedules, dedicated lanes for different modes of transport, and effective traffic management measures. By providing diverse transportation options and facilitating seamless connections between them, the system would distribute the flow of people and vehicles efficiently, mitigating congestion effectively.

Interactions Between Area, Subareas, and Other Areas

Multimodal transportation is highly interconnected with technologies like CAVs, micromobility solutions, and shared mobility. These innovations support first-mile and last-mile travel, creating an integrated transportation network. For example, individuals can use an e-scooter from their office to a bus stop, leave it at a rack, take the bus home, and then use an e-bike to reach their apartment building. E-bikes, e-scooters, shared cars, and rideshare services all contribute to a more efficient and sustainable transportation system.

Shared Transportation Systems

An interview was conducted with one expert specializing in the shared transportation systems field. The professional works for academia. A synthesis of this interview is outlined below.

Definitions and Subareas

Definition

A shared transportation system is a system that includes different modes of transportation that no individual holds ownership of, and everyone can use them. However, for a shared transportation system to be considered "good," lots of components are involved, such as available mode shares and their usage percentages and whether they are connected to each other or to other systems.

Subareas

The subareas of shared transportation systems include micromobility, ride-sharing, ride-hailing, car-sharing, and public transportation. Those subareas can all be part of shared systems and can have an impact on congestion reduction.

Congestion Reduction Strategies, Conditions, and Approaches

It is extremely important to realize under what conditions and situations a shared transportation system in a city can function well and achieve the congestion reduction goal. For example, in a segregated city, individuals in disadvantaged areas may experience issues accessing micromobility because the operating companies fear vandalism. This is a lose-lose situation for both parties since the company will lose potential trips from certain areas. Reliable micromobility used by people to commute to and from work can influence both recurrent and non-recurrent congestion.

Current and Future Technologies

Current Technologies

The whole concept of shared transportation systems and micromobility specifically involves the use of various technologies. Those technologies are advancing.

Benefits, Limitations, and Uncertainties

Benefits

Shared transportation, including carpooling and micromobility, reduces traffic, emissions, and costs while enhancing sustainability. Carpooling decreases commuting time, stress, and expenses, while promoting social interaction. Micromobility provides efficient, eco-friendly alternatives for short trips, improving accessibility, encouraging physical activity, and fostering integrated urban mobility with lower infrastructure costs.

Limitations

Weather and climate conditions can limit the use of shared transportation systems. Safety concerns are also part of the limitations. For example, many states have made it mandatory to use safety equipment when using micromobility options, which few people have. A larger share of users of this mode are men. Elderly people cannot use them. Other limitations of shared transportation systems include the requirement of driver licenses, serving one person per trip, and no specific separate lane.

Looking into the Future and Percent Congestion Reduction

The congestion reduction percentage completely varies. If everything is cost-effective and the mode share percentage is high enough that many people treat it as a reliable mode, then it can reduce congestion by 10 percent (the maximum situation) in a large city.

Telecommuting and Flexible Work Hours

Interviews were conducted with five experts specializing in the field of telecommuting and flexible work hours. The professionals that were interviewed work for regional councils of governments, consulting companies, and academia. A synthesis of these interviews is outlined below.

Definitions and Subareas

Definition

Telecommuting involves relocating the workplace, enabling individuals to perform their tasks from any location equipped with the necessary tools and connectivity. Historically, telecommuting was used as remote access to replace the commute, but now it applies to working anywhere besides the traditional worksite.

The concept of Flexible Work Hours pertains to any work schedule that deviates from established norms governing fixed work hours but still adheres to the required work time. This flexibility extends to variations in starting and ending times, alterations in working hours, and the potential for longer shifts. It serves as an alternative to the traditional 9 to 5, 40-hour work week, offering employees the freedom to adjust their arrival and departure times.

Subareas

Telecommuting encompasses various subareas:

- **Home-Based Telecommuting:** This involves working entirely from home.
- **Regional Office Commuting:** Employees commute to a regional office closer than the main office, resulting in a shorter commute.

Flexible Work Hours subareas include:

- **Compressed Work Week:** This involves working four days a week, with each day consisting of 10 hours, compressing the standard 40-hour workweek.
- **Staggered Work Hours:** This subarea allows individuals to start at different hours, such as 7 to 3 or 9 to 5, providing a more fixed schedule with the flexibility to choose preferred work times. This allows for flexibility, enabling individuals to, for example, work from 6 am to 8 am, take breaks for personal activities, and resume work later in the day. All employees must be present from 9 am to 3 pm, but arrival and departure times can vary between 6 am and 9 am and 3 pm and 6 pm.

Congestion Reduction Strategies, Conditions, and Approaches

Telecommuting offers a potential solution to alleviate congestion by reducing the frequency of commute trips and the overall vehicle miles traveled. Efficient telework implementation can eliminate some trips entirely, and even if travel is still necessary, shorter trips contribute to a reduction in cars on the road, thereby mitigating congestion.

Flexible work hours also play a role in congestion reduction. By compressing work hours, individuals can minimize daily travel, taking cars off the road consistently. Alternatively, flexible hours allow employees to take breaks or conclude work remotely, leading to reduced travel during peak hours and a subsequent decrease in the number of vehicles on the road during congestion-prone times.

For businesses with shift work, where simultaneous arrivals can lead to congestion at entry points, staggering the starting times of work proves beneficial. This strategy helps minimize congestion at entry points, enhancing the overall efficiency of traffic flow on the property.

Regarding congestion, the primary impact is on recurring commute trips during the morning (AM) and evening (PM) peak hours. However, non-recurring congestion, attributed to events like natural disasters, snowstorms, or special occasions such as a World Series game, presents an opportunity for organizations to explore telecommuting. In situations where these infrequent events occur, implementing telecommuting can effectively eliminate the need for trips to specific areas or keep individuals at home, thereby preventing the worsening of congestion and improving overall experiences.

In Telecommuting and Flexible Work Hours, strategies involve implementing a structured program encompassing formalized policies and procedures. This includes defining eligibility criteria and providing training for both employees and managers.

Current and Future Technologies

Current Technologies

The technologies integral to telecommuting often comprise a set of tools such as laptops, cell phones, printer combinations, shared-cost internet access, and video platforms like Zoom and Teams. Additionally, file sharing and cloud computing are crucial in facilitating adequate remote work arrangements.

Future Technologies

In the near future, current technologies will evolve and improve. Employers will decide to invest in telecommuting and flexible work hours. Simultaneously, a substantial number of employees, particularly those favoring flexible work hours, support these strategies. In the future, telecommuting will remain a significant aspect of the work landscape, likely taking the form of hybrid work arrangements.

Benefits, Limitations, and Uncertainties

Benefits

The primary advantage of telecommuting lies in reducing commute trips, particularly during peak hours.

Limitations

The main limitation is that not all jobs are suitable for telecommuting, limiting its widespread applicability. Another challenge is that traditional commuting often involves stops at various places like the post office or grocery store, creating a chain of short trips associated with the main commute. Telecommuting lacks the long trip to anchor these short trips on to, potentially leading to the creation of additional short trips that might contribute to congestion.

Uncertainties

One uncertainty surrounding the impact of telecommuting on congestion hinges on employers' willingness and employees' interest. Employers, through decisions on telework schedules, flexible schedules, and parking policies, wield significant influence on congestion. This influence is often underestimated in terms of how much control there is. For instance, if they don't permit flexible hours for an employee to catch a bus, employees may opt for alternative means, usually a private car.

Another uncertainty arises from full-time telecommuters potentially relocating, contributing to congestion in locations other than their employer's address.

Flexible work schedules introduce a multitude of short trips that were absent in the traditional full-time business location setup, leading to a different kind of congestion. Although the peaks may have diminished, short trips during other periods persist.

The surge in freelance and contractor work further complicates the scenario. Many remote workers no longer adhere to traditional schedules, engaging in projects for different clients and incorporating midday meetings, impacting traffic congestion due to these individuals' varied employment nature and schedules.

Looking into the Future and Percent Congestion Reduction

If everyone has the capability to work from home one day a week, there is the potential to effectively decrease commute trips to and from the workplace by around 20 percent. However, achieving up to a 40 percent reduction is not only plausible but also sustainable.

Interactions Between Area, Subareas, and Other Areas

Telecommuting and Flexible Work Hours are highly compatible with other congestion mitigation strategies. They can be used when employees are required to report to an office. These strategies include multimodal transportation, shared transportation systems, and incident management. For instance, in the event of an incident, an individual who telecommutes or has flexible work hours can adjust their schedule, work remotely, or alter their hours, potentially mitigating congestion following an incident.

Multimodal public transport is another area where telecommuting and flexible work hours can play a significant role. Adapting work schedules to match transit systems or coordinating with transit agencies in specific areas can enhance the advantages of flexible work schedules. Establishing solid connections and information sharing between transit agencies and organizations can make flexible work schedules more beneficial for individuals. This approach supports flexible scheduling and encourages more thoughtful, greener commuting options, reducing dependence on solo driving.

Smart Navigation Systems

One smart navigation expert was interviewed about smart navigation systems. A synthesis of this interview is as follows.

Definition and Subareas

Definition

Smart navigation systems are defined as devices or applications that utilize real-time, live data streams or databases to inform drivers of real-time traffic conditions and offer alternative routes based on congestion levels at the time of travel. These systems differ from traditional navigation tools by providing dynamic updates rather than static directions.

Subareas

While there is no general consensus regarding the subareas, there are generally two main categories: in-vehicle navigation systems and smartphone navigation applications. Both types of systems typically provide similar functions, such as turn-by-turn directions, traffic updates, and alternative routes. However, while both serve similar functions, the smartphone apps are updated more frequently, providing users with the most current information for route optimization.

Congestion Reduction Strategies, Conditions, and Approaches

Smart navigation systems employ various methods to mitigate congestion. They collect live traffic data through crowdsourcing, traffic stations, and probe vehicle data, then use this information to calculate alternative routes for drivers, ultimately reducing individual delays and congestion. However, current systems primarily benefit individual users rather than addressing congestion at a system-wide level.

These systems are particularly effective in addressing non-recurring congestion caused by incidents, as they can quickly inform users of alternative routes in real time. The effectiveness of smart navigation systems in reducing congestion depends on a number of factors, including:

- **The accuracy of the traffic data.** Smart navigation systems rely on accurate traffic data in order to provide useful information to drivers.
- **The number of people who use smart navigation systems.** The more people who use smart navigation systems, the more effective they will be in reducing congestion.
- **The willingness of drivers to follow the directions provided by smart navigation systems**. Smart navigation systems can only be effective if drivers are willing to follow the directions they provide.

Overall, smart navigation systems are a valuable tool that can be used to reduce congestion. However, they are most effective when they are used in conjunction with other congestion reduction strategies.

Current and Future Technologies

Current Technologies

Currently, smart navigation systems rely primarily on cellular connections to gather traffic data, although satellite technology such as Sirius XM also plays a role. In terms of the end-user, smartphone applications are a common type of smart navigation system. These applications use cellular data to connect to online services that provide traffic information. For example, Google Maps and Waze are popular smartphone navigation applications that provide real-time traffic updates. In-vehicle navigation systems are another system that is built into vehicles and provides drivers with turn-by-turn directions and traffic information. These systems typically use cellular data to connect to online services that provide traffic information.

Future Technologies

Looking ahead, an evolution of vehicle-to-vehicle communications and increased integration of additional data sources, such as connections to signalized intersections is expected. These advancements aim to enhance the effectiveness of smart navigation systems in mitigating congestion both now and in the future. Some of the future enhancements could include:

- **Vehicle Connectivity**: Improved vehicle connectivity will allow smart navigation systems to communicate with each other and with traffic infrastructure. This will enable vehicles to share real-time traffic data, such as accidents, road closures, and traffic congestion.
- **Enhanced Data Collection Methods**: Enhanced data collection methods will allow smart navigation systems to collect more accurate and timely traffic data. For example, sensors and cameras can be used to collect data on traffic volume, speed, and travel times.
- **Integration with Traffic Signals**: Integration with traffic signals will allow smart navigation systems to optimize traffic flow. For example, smart navigation systems can communicate with traffic signals to adjust the timing of lights to reduce congestion.
- **Vehicle-to-Vehicle Communications**: The evolution of vehicle-to-vehicle communications will enable vehicles to communicate with each other directly. This will allow vehicles to share information about their location, speed, and direction of travel. This information can be used to improve traffic flow and safety.
- **Integration of Additional Data Sources**: Smart navigation systems will be integrated with additional data sources, such as weather data and public transportation data. This will allow smart navigation systems to provide drivers with more comprehensive information about traffic conditions.

Benefits, Limitations, and Uncertainties

Benefits

Smart navigation systems provide several benefits to drivers. One key benefit is that they offer alternative routes to drivers, allowing them to avoid congested areas and save time. Additionally, these systems can potentially reduce congestion by distributing traffic more evenly across different routes. Smart navigation systems can also provide real-time traffic updates, helping drivers make informed decisions about their routes and avoid delays. Furthermore, they can suggest fuel-efficient routes, reducing fuel consumption and emissions.

Limitations

The effectiveness of smart navigation systems is dependent on drivers following the suggested routes. However, drivers may choose to ignore these routes due to factors such as personal preferences, familiarity with alternative routes, or a desire to avoid potential delays or traffic congestion. This undermines the system's ability to optimize traffic flow and reduce congestion. Additionally, traffic conditions can change rapidly due to unexpected events like accidents, road closures, or sudden changes in weather. Smart navigation systems may not be able to adjust to these changes in real time, leading to outdated or inaccurate route suggestions. This can result in drivers experiencing longer travel times or encountering unexpected traffic congestion.

Uncertainties

Despite the potential benefits of smart navigation systems in reducing traffic congestion, uncertainties remain regarding the exact percentage of congestion that can be attributed to their use. This is due to several factors, including the varying levels of adoption and usage of these systems among drivers, the variability in traffic patterns and conditions, and the limitations of the systems themselves. The effectiveness of smart navigation systems is also influenced by factors such as the accuracy and timeliness of traffic data, the algorithms used to calculate routes, and the compliance of drivers with suggested routes. As a result, it is difficult to precisely quantify the impact of smart navigation systems on congestion reduction.

Looking into the Future and Percent Congestion Reduction

While technology can help reduce congestion, it will continue to persist as long as there are vehicles on the road. The expected range of congestion reduction from smart navigation systems in the future is between 10 percent and 30 percent. However, the actual percentage of reduction will depend on various factors, such as the level of penetration of smart navigation systems, the accuracy and timeliness of traffic data, and the integration of smart navigation systems with other traffic management strategies.

Interaction Between Area, Subareas, and Other Areas

Smart navigation systems interact with various congestion mitigation areas, including connected and automated vehicles, public transportation systems, incident management, and congestion pricing. This interaction can potentially enhance the effectiveness of these systems in reducing traffic congestion. However, challenges exist in integrating these systems due to differences in their methods, data sources, and integration processes.

Efforts are underway to streamline the collaboration between smart navigation systems and other congestion mitigation areas. This includes the development of standardized data formats and communication protocols, as well as the establishment of partnerships and alliances between stakeholders. These efforts aim to overcome the challenges of integration and unlock the full potential of smart navigation systems in reducing traffic congestion and improving transportation efficiency.

Public Transportation Systems

Interviews were conducted with six experts specializing in the field of public transportation. The professionals work for metropolitan planning organizations, transportation agencies, and academia. A synthesis of these interviews is outlined below.

Definitions and Subareas

Definition

PT is defined as a service to the public and to the community that a public transportation system is based around, and it can be provided using different modes. It involves the movement of larger numbers of people. The definition might shift to include on-call transportation services used to address the last and first mile (Uber, Lyft).

Subareas

Subareas within public transportation can be defined in several ways:

- **Technology:** Differentiated by the technology employed, such as bus, rail, subway, streetcars, or light rail.
- **Service recipient:** Categorized based on the demographic served, whether it is local, regional, or national populations.
- **Social Aspect:** Distinguished by social considerations, addressing areas with transit-dependent populations lacking personal vehicles or those with choice riders who opt for public transport despite having cars.
- **User Types:** Varies based on the users, including Paratransit services that are publicly funded to support specific needs.
- **Route Structure:** Characterized by the route structure, encompassing fixed routes and shuttle circulator services.

Congestion Reduction Strategies, Conditions, and Approaches

In PT, the primary focus is identifying areas of high activity where people originate and determining their destinations to devise effective solutions. While congestion can act as a motivating factor, it is essential to distinguish PT's role as a congestion management tool rather than a mitigation tool, particularly in urban sprawl areas or mixed traffic scenarios.

Key considerations include:

- **Congestion Management:** Buses operating in mixed traffic may face congestion, but railroads and subways, with dedicated routes, can navigate traffic and contribute to congestion management.
- **Mitigating Congestion:** PT has the potential to significantly mitigate congestion in densely populated areas like New York or Washington DC. Even with effective PT systems, these large cities may still experience congestion. Without the systems, traffic congestion could be very serious.
- **Special Events**: PT becomes instrumental during special events when drivers park their cars, opting for buses to complete the final leg of their journey.

- **Fixed Guideway Impact:** The use of fixed guideways, such as dedicated lanes for buses or light rail, theoretically contributes to congestion reduction, especially in high-traffic movements like downtown areas, cruise businesses, or tourist routes between hotels, airports, and seaports.
- **Recurring and Non-recurring Congestion:** PT, with its ability to carry more people and offer safer transportation, has the potential to reduce both recurring congestion, as seen in downtown areas, and non-recurring congestion during events like air shows.

Current and Future Technologies

Current Technologies

There are a variety of technologies used in PT area:

- Transit Signal Priority gives priority to buses at intersections.
- Paying fares using the phone.
- Zero-emission buses.

Future Technologies

- **Short-term**: The adoption of electronic payments contributes to the increased safety of bus drivers, eliminating the need for handling cash transactions. Small transportation agencies will embrace the technology pioneered by larger agencies, promoting a more widespread adoption of electronic payment systems, improving the user experience of applications. The current challenge lies in the fragmentation caused by each agency having its own application, making cross-regional travel complex. The incorporation of electronic payments facilitates the expansion of available rides, thereby enhancing mobility options for commuters. The move towards fully electronic payments signifies a higher level of automation within the public transportation system, streamlining processes and improving overall efficiency.
- **Medium-term**: Full electrification.
- **Long-term**: Driverless buses, air urban transportation, flexibility on demand.

Benefits, Limitations, and Uncertainties

Benefits

Rail systems have the potential to alleviate congestion significantly due to their high capacity, but their implementation is costly and feasible primarily in densely populated areas. On the other hand, strategic utilization of buses, with flexible route planning, holds promise as a more adaptable and cost-effective solution.

Limitations

Public transportation's effectiveness in congestion mitigation is compromised when it operates in mixed traffic. Collaborations between transportation agencies and ride-sharing services like Uber, while providing door-to-door service, can paradoxically contribute to increased congestion, as these vehicles add to street traffic without necessarily reducing the number of individual cars on the road. Additionally, the implementation of light rail and heavy rail systems entails considerable costs, posing a significant challenge to their widespread adoption.

Uncertainties

The advancement of public transportation relies heavily on political determination and the need to overcome negative perceptions associated with public transportation.

Looking into the Future and Percent Congestion Reduction

The objective is to sustain the existing level of congestion, acknowledging the inherent challenges for PT to single-handedly address congestion issues. The interactions between different areas, subareas, and other related components play a crucial role in achieving this goal.

Interactions Between Area, Subareas, and Other Areas

PT aligns with other congestion mitigation areas, encompassing congestion and road pricing, smart and advanced signal timing and optimization, TSM&O, incident management, telecommuting and flexible hours, smart navigation systems, and shared transportation systems.

Congestion and Road Pricing

Two experts were interviewed to discuss congestion and road pricing. The experts brought their experience from academia and the consulting field. The project team coordinated the teleconferences and facilitated and documented discussions.

Definitions and Subareas

Definition

Congestion pricing is a strategy implemented in large or very large metropolitan areas to alleviate traffic congestion by imposing tolls or fees on vehicles using certain roadways during peak hours. This approach aims to manage demand for road usage by encouraging alternative transportation methods or travel times, thus reducing congestion. It involves setting variable prices for road usage based on time of day or level of congestion, with the intention of influencing travel behavior and improving traffic flow.

Subareas

There are three subareas that highlight the multifaceted nature of congestion pricing, incorporating modeling and analysis, implementation strategies, and equity considerations in the design and execution of congestion pricing schemes.

- **Modeling and Analysis**: This involves conducting complex modeling and analysis to understand the potential impacts of congestion pricing on traffic patterns, carpooling behavior, and overall congestion levels. However, the interview suggests that political circumstances sometimes hinder the effectiveness of these models.
- **Implementation Strategies**: This encompasses the strategies and approaches used to implement congestion pricing schemes, such as proposing pilot programs, considering public perception, and addressing equity concerns. It also involves navigating political challenges and seeking funding opportunities.
- **Equity Considerations**: This subarea focuses on addressing equity implications associated with congestion pricing, including the impact on low-income residents and communities, as well as

strategies to mitigate inequitable impacts. Examples include offering reduced tolls for low-income residents and considering the fairness of tolling structures.

Congestion Reduction Strategies, Conditions, and Approaches

Congestion reduction strategies involve implementing road pricing schemes to manage demand and mitigate congestion. These schemes aim to address specific spot improvements but may not have a systemic impact due to complex funding structures in the United States. Equity considerations are crucial in designing road pricing schemes, with efforts made to mitigate inequitable impacts through strategies such as offering reduced tolls for low-income residents. Public perception of fairness plays a significant role, with challenges arising from the lack of understanding of public finance and concerns about additional taxes. Flexibility in policy design, including adjustments based on feedback and political context, is essential for successful implementation. Despite challenges, lessons learned from past implementations, such as the need for clear communication and stakeholder engagement, provide valuable insights for future initiatives.

Current and Future Technologies

Current Technologies

These technologies encompass various tolling systems, including cameras, readers, infrared devices, loop detectors, and vehicle occupancy detection systems, designed to facilitate toll collection and ensure effective traffic management. The technologies can be divided into roadside and in the vehicle technologies.

Future Technologies

Technologies like various types of algorithm technologies and ML are used to address congestion, as well as high resolution and infrared image cameras. Applications that ensure people riding in the same vehicle are using the HOV lanes. There are some agencies and private firms that are starting to try and pilot and test some of the AI technology, the ML components to better understand the conditions and better understand what impact rates truly affect drivers versus people making up their minds already before they even get to that to the facility.

The value of big data will continue to grow as more facilities join in to comprehend the variations among different types of facilities and users. This includes understanding how users respond to congestion road pricing components such as tolls, HOV policies, usage types, and the types of vehicles permitted.

Benefits, Limitations, and Uncertainties

Benefits

Congestion pricing schemes have the potential to alleviate traffic congestion by incentivizing changes in travel behavior, such as carpooling or adjusting travel times. This effect was evident in the initial increase in carpooling numbers following the introduction of tolls. These schemes can address both recurring and nonrecurring congestion, depending on the policies implemented.

Facilities with static pricing, similar to traditional toll systems, are typically effective in managing recurring congestion during predictable periods, such as morning rush hours (e.g., 7:00 AM to 9:00 AM) and evening peak times (e.g., 4:00 PM to 7:00 PM). In contrast, facilities employing dynamic pricing, which adjusts rates based on real-time congestion levels, can better manage nonrecurring congestion. For instance, dynamic pricing can respond to unexpected events, such as traffic incidents or large gatherings, by adjusting tolls to mitigate congestion efficiently. Additionally, congestion pricing programs have the potential to generate revenue that can be allocated to various public projects, providing an opportunity to fund transportation infrastructure improvements and other initiatives.

Limitations

Despite its potential benefits, congestion pricing faces several limitations and challenges. One major limitation is the complexity and difficulty in accurately predicting the outcomes of congestion pricing models, as highlighted by the discrepancies between projected and actual impacts observed in previous implementations. Allowing too many types of vehicles could potentially saturate managed lanes and make it a lot more challenging to manage congestion. Moreover, the political climate and public perception can significantly influence the feasibility and acceptance of congestion pricing schemes, as seen in the challenges faced during the planning and implementation stages of the Bay Bridge toll project.

Uncertainties

Several uncertainties surround the implementation and effectiveness of congestion pricing schemes. One key concern is the equitable distribution of the toll burden and public perceptions of fairness, especially for low-income residents and reverse commuters. Addressing these concerns requires careful consideration and innovative solutions. Additionally, the broader implications of congestion pricing on transportation funding and policymaking remain unclear, particularly its potential for systemic change versus localized solutions. These uncertainties highlight the need for further research to assess the long-term impacts and feasibility of congestion pricing initiatives.

Looking into the Future and Percent Congestion Reduction

Looking into the future of road pricing and the potential for congestion reduction presents a complex landscape shaped by political, social, and economic factors. While past attempts at implementing congestion pricing, such as the Bay Bridge toll project in the 2000s, have encountered challenges and yielded mixed results, there remains a continued interest in exploring road pricing schemes as a means to address traffic congestion.

Appropriately designed road pricing schemes have the potential to reduce congestion by 20 to 25 percent. However, if all vehicles are granted access without restrictions, the reduction in congestion will be less significant.

Interactions Between Area, Subareas, and Other Areas

There are intricate dynamics among different facets and sub-categories within congestion pricing, revealing the intersection of modeling and analysis, implementation strategies, and equity considerations. The insights received illuminate the hurdles faced when utilizing sophisticated models to forecast congestion impacts, particularly when political factors impede their efficacy. Furthermore, it is important to address public sentiment and equity issues during implementation, advocating for measures like discounted tolls for low-income communities to alleviate unequal repercussions. This amalgamation of diverse subareas accentuates the multifaceted nature of congestion pricing schemes, necessitating a nuanced approach that balances technical analyses, political exigencies, and social fairness to achieve successful outcomes.

Connected and Automated Vehicles (CAVs)

Four CAV experts were interviewed on how CAVs can be used to reduce congestion. Information on definitions, technologies, and examples are also inquired from those experts. A synthesis of all four interviews is as follows.

Definition and Subareas

Definition

Connected and automated vehicles are distinct concepts. A connected vehicle communicates with other vehicles and surrounding infrastructure to exchange information, enhancing safety and improving the efficiency of travel for all road users along the corridor. Automated vehicles operate either with a human driver or through self-driving systems. These vehicles can serve as either a partial or full replacement for human drivers, utilizing automatic control systems. Full replacement corresponds to high-level automation, while partial replacement or driver assistance includes features like adaptive cruise control and automatic lane control (such as lane keeping and lane changing). Although an automated vehicle may also be connected, a connected vehicle is not necessarily automated.

Subareas

There are different ways to divide CAV technologies. One way is using spatial and temporal scales in the following order:

- First is a network level, such as routing and recommending travel plans, network management and coordination technologies, including carpooling or others to reduce vehicle miles traveled, connectivity is at a network level. Ensuring that traffic is distributed effectively across different routes, both spatially and temporally, to avoid overconcentration.
- The second aspect involves facility-level and segment-level measures, including coordination with traffic signals and speed harmonization. These strategies can mitigate the effects of bottlenecks, maintain capacity, prevent capacity drops, and minimize the impact of all-red times and clearance intervals at intersections. The third level is vehicle level. This involves platooning, cooperative lane changing that can help reduce congestion by improving the efficiency of microscopic maneuvers like car following and lane changing. Car following can reduce the headways and lane changing can reduce potential conflicts.

The general subareas of CAVs include vehicles talking to each other, vehicles talking to infrastructure, the infrastructure talking back to the vehicles, and vehicles talking to other things. They can also be classified as:

- Vehicle to vehicle (V2V),
- Vehicle to infrastructure (V2I),
- Vehicle to everything (V2X).

CAVs could also be categorized as passenger CAVs versus private CAVs, slow moving CAVs for services, PT, shared CAVs (e.g., shuttles), and freight CAVs.

Congestion Reduction Strategies, Conditions, and Approaches

The various CAV strategies and approaches that can be used to help with congestion include the following:

- **Connectivity**: Passing information along so people can make better or different route choices is important to reduce congestion. Getting information to motorists before they get into traffic or managed lanes enables drivers to take alternate routes. CAVs can also help communicate LOS to vehicles (trucks), which can help reduce recurring congestion.
- **Platooning**: This strategy involves a driving approach in which multiple CAVs form a coordinated "platoon." These vehicles travel in close proximity, leveraging vehicle-to-vehicle communication to maintain precise spacing and enhance traffic flow. This method increases road capacity and improves efficiency, particularly on highways with minimal disruptions. This can be done safely and efficiently with CAV technologies by improving communication between vehicles. Platooning can help improve capacity and movement of vehicles in seamless fashion, but in mixed traffic automated vehicles face challenges because they are fully relying on in-vehicle sensors.
- **Speed harmonization**: This process involves determining the optimal speed for individuals to navigate a corridor. This speed is not necessarily the fastest but is designed to maximize the efficient flow of vehicles through improved connectivity. Artificial Intelligence (AI) and Machine Learning (ML) technologies can facilitate speed harmonization and encourage drivers to maintain these optimal speeds.
- **Traffic incident management:** Ha the potential to reduce the number of crashes (secondary crashes), which can also reduce delays and non-recurring congestion.
- **Shared CAV rides:** These can be beneficial for dense places. Automated transit or shared CAVs could help with congestion by transporting more people in buses. It can also help with setting transit priority for transit.
- **Small and compact vehicles and microtransit:** These could also be used to mitigate the impact of congestion.

Speed harmonization and platooning can mitigate recurring congestion and stabilize day-to-day traffic flow. Traffic incident management and special event management can help with non-recurring congestion. CAVs can help reduce non-recurring congestion by reducing crashes. During special events and emergencies, CAVs can help manage traffic. However, for recurring congestion, it can either reduce or increase congestion. CAVs can help with the value of time and eligibility of driving, which can increase traffic congestion.

Current and Future Technologies

Current Technologies

The current technologies used in CAVs are cameras, radars, GPS, and vehicle sensors. For automation, the technologies are for perception and control (prediction). For connected, the technologies are communication, including dedicated short-range communication (DSRC), CV2X, and long-range communication. Detection systems are important for communication. For network, technologies are about communication and connectivity. For the segment and vehicle levels, technologies are about integration of communication and automation. Automation becomes more and more important down the scale, such as at vehicle levels.

For the existing fleet, at least 10 percent of vehicles already have ACC functions, level 1 or level 2 automation, and 92 percent of newly produced vehicles have level 1 or level 2 automation. As more vehicles have automation functions, they will replace the old fleet.

Future Technologies

In the short run, CAV technologies will evolve in urban areas and comprise roadside unit infrastructures (boxes). In the medium to long run, these technologies will expand to rural areas. This may take a while because of constraints and resource availability. Connected vehicles will be based not only on roadside infrastructures but also on satellite technologies. This can help in rural areas where information can be transferred by satellite to vehicles.

In the medium to long term, automation levels are expected to advance significantly. Level 3 automation has already been commercialized in Germany, and within five years, a growing number of vehicles are likely to adopt this technology. However, it will take decades to replace the existing fleet with vehicles equipped with Level 3 and higher automation technologies. Furthermore, Level 3 automation may remain limited to specific operational domains, such as freeways and favorable weather conditions, which will constrain its deployment scale and applicability.

In the next 6 to 19 years, some vehicles may incorporate Level 4 automation. However, achieving Level 5 automation, which represents full autonomy under all conditions, is expected to take considerably longer. When looking into the future, the following could also be stated:

- **Short-term**: More states will experiment with CAVs, and people will become more knowledgeable and believe in the technologies. States like Florida, Georgia, Pennsylvania, Virginia, Utah, and California are already experimenting with CAV technologies through various projects.
- **Medium-term**: More focus will be on the data platform.
- **Long-term**: More connectivity will be expected with car companies.

The technologies could also be subdivided as follows:

- **Freeways**: Queue warning, speed advisory, work zone apps, incident clearance, detour details, freight priority (truck platooning), wrong-way detection, curve warnings, speed guidance.
- **Arterials**: Signal coordination, ATSPM, adaptive signal technologies, transit and freight signal priority, emergency vehicle preemption, railroad.
- **Vehicles**: Lidar, camera, GPS, radar.

Benefits, Limitations, and Uncertainties

Benefits

CAVs have many current and future benefits. Automated features can help save time for important things like meetings or taking care of kids. They can help transportation in disadvantaged communities. Overall, while automated vehicles offer significant benefits, their integration with connected technologies enhances their effectiveness. The biggest benefits of CAVs include reducing human cognition failure (DUI), lane departure warnings, blind spot warnings, work zone safety improvement, and secondary crashes decrease (reduction in congestion, reduction in queues, speed drops).

Limitations

To efficiently operate automated vehicles in mixed traffic (automated vehicles recognizing non-automated vehicles) or designing dedicated lanes for automated vehicles will require a large scale and may take several years. Thus, until enough automated vehicles are available, it does not make sense to build a road just for automated vehicles because that road would sit empty. The availability of big and smart data may also be one of the limitations. Thus, the limitations include:

- The maturity of technologies.
- Government perspectives.
- Private consumers' perceptions.
- Technology will help, but the limitation is people entirely relying on them.
- Infrastructure, detection, and communication need to be upgraded for better results.
- Connectivity to remote areas may also be a challenge.
- In the connected vehicle environment, the biggest challenges are due to the coverage of the network of the connected vehicle infrastructure, especially the coverage of CAV infrastructure outside of vehicles. This coverage can affect communication between vehicles and the infrastructure.

The interoperability issue is another challenge since different states are doing things differently regarding how CAVs are deployed and accepted. To increase the adoption and penetration rate, a vision at the federal government level will be required. As part of the limitation, there would probably be competing elements in urban areas. Therefore, when tackling congestion using CAV technologies, setting priorities will be important. For example, priorities should be set to prioritize the movement of people or goods in case of congestion. Thus, using CAVs will require tradeoffs.

Uncertainties

Uncertainties exist in vehicle-to-vehicle and vehicle-to-infrastructure systems, where vehicles must take control, raising questions about public acceptance and liability. From a safety standpoint, it is unclear whether people will trust automated vehicles to stop or slow down when approaching a stop sign or driving too fast.

The adoption of CAV technologies will be slower if market-driven, as some manufacturers may opt out, while others invest. Regulatory and institutional processes often lag behind technology, impacting adoption rates. Connectivity also faces uncertainty, relying on government investment, as private companies are hesitant to fund it. Collaboration with cellular operators may be needed, with incentives to encourage participation. Additionally, it is uncertain how CAV technologies will affect long-term congestion and adaptability.

There are a few other uncertainties such as:

- Infrastructure readiness (e.g., signals being ready for connectivity).
- People’s willingness to adopt the technologies (e.g., for elder user community, it will be important to know if elders are ready to use these technologies).
- Institutional readiness (e.g., not every state is ready to implement, implementing the technologies will require tools and adequate human resources with trained manpower, it will involve cost, viability (long term), operations and maintenance, and skilled labor).

Looking into the Future and Percent Congestion Reduction

If automated vehicles are the way of the future, they will start getting momentum and ramp up to the point whereby long-term (16 to 20 years) management of lanes for CAVs will be possible because of the increased number of automated vehicles. Platooning or speed harmonization can get up to 20 to 30% more vehicles through the same system using CAV technologies.

For Recurring Congestion, CAVs can help reduce congestion at a network level up to 30 percent and at a facility level up to 50 percent. Recurring congestion can be the negative effect of high penetration of CAVs. For example, people might decide to engage more in leisure-type activities or to live far away because of CAVs.

For Non-Recurring congestion, CAV can reduce up to 90 percent of non-recurring congestion. For example, with CAV, people can have access to real-time and high-frequency data to adjust traffic and address congestion. Professionals can use this data from vehicles when a crash happens to inform incoming vehicles on affected corridors about a crash and suggest a driving speed for clearing the queue near the crash.

Predicting the adoption rate of CAVs is challenging because it depends not only on technology but also on the regulatory environment and the consistency of technology adoption across states. If experts leverage past and present experiences, a 30 percent adoption rate could be achievable in the next 20 to 25 years, especially for private vehicles. While full automation may not be reached, Level 4 automation could be realized. Adoption rates will also depend on the penetration of electric vehicles and the types of technologies used, such as the shift from dedicated short-range communication to 5G for vehicle connectivity.

A combination of strategies may yield better outcomes. For instance, while speed harmonization alone may have a limited impact on non-recurring congestion, pairing it with dynamic rerouting could be more effective. This would allow drivers to receive alternate route suggestions to avoid congestion, demonstrating that adoption rates are influenced by the integration of various solutions.

Interaction Between Area, Subareas, and Other Areas

CAVs can be integrated into all 12 subareas, though not everything can be automated. While smart and navigation systems are integral to CAVs, telecommuting and flexible work hours are less directly related. Congestion and road pricing are somewhat connected, with road pricing becoming essential for infrastructure management as fuel taxes decline. User-based systems and road pricing will be critical. Connected technologies can enhance PT, smart signal timing, and TSM&O strategies. Automation could improve signal timing, phasing, and incident management—for instance, through automated vehicles patrolling and identifying incidents. Multimodal and smart navigation systems are also interconnected with CAVs.

Certain roadways are more suited for automation. Highways and signalized arterials are ideal for reducing congestion, with platooning vehicles showing promise in these areas. For collectors and dedicated roadways, freight movement via automated vehicles is more relevant. Urban and suburban areas facing recurring congestion are better suited for CAV technologies than rural areas, where safety is a more significant concern. In rural regions, CAVs can help reduce crashes, while urban areas benefit from reduced congestion during peak hours. For non-peak hours, CAVs address non-recurring congestion. In central business districts, automated ridesharing and freight systems will play a significant role, especially where large areas or freight miles are involved.

Advanced Transportation Technologies

Definitions and Subareas

The concept of advanced durability focuses on emerging aviation markets and use cases for urban, suburban, and rural operations. Urban Air Mobility is the same concept but limited to urban and suburban built environments within a 50-mile radius. It can include passenger mobility, logistics, emergency services, and professional use cases. eVTOL vehicles can bypass ground congestion, reducing travel time by traveling vertically with a maximum speed of 150 miles per hour and carrying up to four passengers.

Congestion Reduction Strategies, Conditions, and Approaches

UAM and Advanced Air Mobility (AAM) can potentially reduce surface traffic congestion, but they may not be effective during the early implementation stage, despite popular narratives like Uber Elevates. The services may be costly and have limited infrastructure, making them impractical for various trip types. Additionally, shifting travel from surface transportation to AAM or UAM could relocate congestion without reducing it in the early deployment stages. UAM can find niche applications in goods delivery and logistics, but its economic scale diminishes compared to more established modes like railroads and surface trucks. UAM can offer value in serving remote locations with limited accessibility through traditional roadways. However, it may not significantly shift people from trucks to UAM for mass transportation. Nevertheless, if a large proportion of users take UAM, it can reduce the number of vehicles on the ground, releasing ground congestion.

To address congestion effectively, achieving high occupancy is crucial for both passenger and cargo transportation. Current industry aircraft, often limited in impact due to their small capacity, fall short even when fully occupied. "Lilium" proposes scaling up their aircraft to carry sixteen passengers, comparable to a bus, presenting a potential game-changer in tackling congestion challenges. In broader research on UAM in the San Francisco Bay area, 76 vertiports were considered as a starting point. The focus was on showcasing the upper limit of UAM capacity, indicating its potential impact on congestion relief. By analyzing 3 million trips during rush hours, the study revealed that with 76 vertiports, UAM could serve 38,000 passengers per hour, significantly alleviating ground congestion. However, it was noted that local vertiports might experience congestion due to increased passenger attraction.

Current and Future Technologies

Current Technologies

The industry is still in its early stages, with aircraft having limited ranges and relatively small passenger or payload capacities. Currently, it primarily serves the niche of a quieter helicopter.

New aviation services are being developed, but they are not yet utilizing truly innovative aircraft. However, there are numerous prototypes of eVTOL aircraft in the market that are focused on improving their capabilities. For instance, the JOBY S4 has demonstrated an impressive noise reduction.

Future Technologies

Over the next five years, the focus will be on testing new aircraft concepts using existing infrastructure. The industry is expected to witness innovations such as the utilization of hydrogen, larger aircraft with increased payload capacity, and other advancements. As a demonstrated business model emerges, there will likely be a more extensive build-out of infrastructure in the longer term.

Regarding the UAM service, it may become possible in the next decade or 15 years. A lot of investments have been made in this area, and the adaptation rate for UAM may rise in the mid-term or long-term. However, there is still a lot of uncertainty surrounding the viability of UAM.

Limitation and Uncertainties

Various factors such as cost, affordability, aircraft size and capability, range, and turnaround time (i.e., recharging) play a crucial role in shaping the business model for UAM services. A tight turnaround time is necessary, as it not only affects operating costs but also impacts the efficiency of the service for consumers. As UAM technology becomes more advanced, the need for policies and regulations regarding its use by the public becomes increasingly important.

Interactions between Area, Subareas, and Other Areas

Advanced transportation technologies encompass areas like shared transportation systems, incident management, multimodal transportation, and smart navigation systems. UAM and hyperloop require other modes of transportation to get to the vertiports, or hyperloop stations, including bikes, e-scooters, and carpools. Incident management and smart navigation systems enable effective routing and incident clearance near the stations to reduce congestion.

Emerging Technologies

Definitions and Subareas

Definition

Emerging technologies are those currently in the phase of undergoing research and development, potentially for implementation in the next 10-15 years. Examples include hyperloop, automated eVTOL aircrafts, flying cars, and Maglev trains. UAM, including eVTOL aircrafts and flying cars, will be a key area of focus, with significant progress in both policy development and technological advancements. While these technologies may not always mature, ongoing efforts suggest promising possibilities for the future.

Subareas

Potential subareas include UAM (eVTOL and flying cars), hyperloop systems, and Maglev trains, all of which are currently undergoing testing. Additionally, developments like alternative fuel systems for eVTOLs and automated eVTOLs are expected to be implemented within the next 5–10 years. UAM sits at the intersection of advanced transportation systems and emerging technologies, making it a highly relevant and trending topic. The experts interviewed on emergency technologies particularly emphasized UAM, so this section will focus primarily on its developments and implications.

Congestion Reduction Strategies, Conditions, and Approaches

UAM services could revolutionize transportation, initially through service-provider-owned eVTOLs. In the future, wealthy households might own these vehicles, enabling direct flights from rooftops or backyards—a speculative but promising concept. This shift would mark a major intersection of advanced and emerging technologies.

OEMs like Joby Aviation and Archer Aviation have submitted FAA certification applications, suggesting potential approvals in the near future. Engineering firms are also exploring vertiport construction, acquiring land from airports, cities, or private owners. Vertiports, resembling helipads, feature takeoff and landing pads, staging areas for passengers, and charging facilities, eliminating the need for traditional runways.

With established vertiport infrastructure, UAM could alleviate congestion on freeways and expressways, especially for long-distance super-commuters. However, it may strain arterials and residential roads due to population shifts, requiring demand management. While UAM offers significant potential, affordability challenges could limit daily use. Experts suggest UAM is best suited to address rush-hour congestion, with limited data available to assess impacts on non-recurrent bottlenecks.

Current and Future Technologies

Current Technologies

Emerging technologies like eVTOL aircraft and Maglev trains are transforming urban mobility by addressing congestion and enhancing transportation efficiency. eVTOLs, resembling shared mobility services, offer on-demand air travel from compact vertiports equipped with landing pads and charging facilities. Initially piloted with ground operator support, these aircraft may evolve toward greater autonomy, reducing costs and alleviating traffic congestion on busy highways. Construction and service companies are investing in vertiport infrastructure to support this shift, signaling a significant leap in urban transportation innovation.

Future Technologies

Driving and flying vehicles, often referred to as flying cars, are a promising technology currently under exploration, with various OEMs developing prototypes. However, these vehicles face the unique challenge of meeting both roadway and aviation safety standards. Balancing weight and durability is particularly complex—vehicles must be light enough for efficient flight yet durable enough to pass crash tests for road safety. Additionally, the size and design of propeller systems present obstacles to road compatibility, as they may not easily fit standard lanes or infrastructure.

The Federal Aviation Administration (FAA) has proposed air corridors resembling highways, with vertical flight levels instead of horizontal lanes, to accommodate such vehicles. While traditional flying cars have existed for years, most require runways for takeoff and lack vertical takeoff and landing (VTOL) capabilities. The transition toward electric propulsion systems marks a departure from traditional combustion engines, with advancements in hydrogen-powered engines and hybrid systems combining hydrogen for takeoff and electricity for cruising. This evolution aligns more closely with eVTOL air mobility, which prioritizes shared transit services over individual ownership. Despite some proven prototypes, progress remains slow due to technical, regulatory, and infrastructure challenges, leaving the full potential of these innovations yet to be realized.

Benefits, Limitations, and Uncertainties

Benefits

Implementing eVTOLs, flying cars, hyperloops, and Maglev trains offers notable benefits, including reducing congestion caused by private and ground vehicles. These advanced technologies, powered by electric or hydrogen systems, are environmentally friendly alternatives that could significantly lower greenhouse gas emissions. Additionally, eVTOLs and similar aircraft have the potential to replace helicopters, offering quieter operations and helping reduce noise pollution in urban and suburban areas.

To ensure their safe integration into airspace and daily use, these emerging aircraft must undergo rigorous testing, typically requiring 150–200 flight hours. This testing is crucial for demonstrating reliability, safety, and performance, which are necessary for certification by aviation authorities such as the FAA. Achieving these standards will be a critical milestone for their widespread adoption.

Uncertainties

The implementation of advanced technologies like eVTOLs and hyperloops faces numerous uncertainties in policy and planning. A critical concern is cybersecurity, as these systems could be vulnerable to attacks that compromise backup or redundant systems. Mitigating such risks requires robust strategies to safeguard operations and ensure system integrity. Another significant challenge involves determining optimal vertiport locations while addressing infrastructure issues related to battery charging and backup systems. These uncertainties underscore the importance of comprehensive planning, resilient cybersecurity measures, and strategic infrastructure development to ensure the safe and effective integration of these technologies into urban environments.

Limitations

Driving and flying vehicles face significant challenges in balancing roadway and aviation safety standards. Weight optimization for crash safety versus flight performance is a key issue, while large propeller systems complicate road compatibility. The FAA's proposed aerial corridors aim to address these concerns with vertical flight levels. While traditional flying cars require airfields, advancements in electric propulsion and vertical takeoff capabilities show promise. eVTOL air mobility prioritizes shared transit services but faces hurdles such as high costs, long development timelines, and pilot licensing requirements. These factors continue to limit widespread adoption despite technological progress.

Looking into the Future and Percent Congestion Reduction

UAM has the potential to reduce congestion by an estimated 20 percent to 30 percent. In contrast, flying cars and similar emerging technologies are projected to have a more limited impact, likely no more than five percent. This modest outlook stems from significant uncertainties in their design and implementation, which currently constrain their ability to effectively address congestion on a larger scale.

Interactions Between Area, Subareas, and Other Areas

UAM is a major representation of emergency technologies. UAM introduces a shared transportation model that includes both public and private modes. It supports multimodal integration, enabling seamless connections between ground transportation and vertiports for aircraft or drone use. UAM also interacts with systems like incident management and smart navigation, particularly for flying cars. For example, navigation systems could receive alerts about traffic incidents, prompting a transition from driving to flying to avoid delays. Flying cars represent a natural progression of connected and automated vehicle technology, pushing the boundaries of innovation in transportation and enhancing adaptability across various mobility systems.

Chapter 4. Congestion Reduction Roadmap and Resource Guide

The summary of the literature review and interviews conducted as part of this project reveals that traffic congestion can happen for different reasons. For example, it occurs when there is an excessive number of vehicles on the road network, leading to a decrease in traffic speed and flow. It can also happen due to inadequate road capacity or poorly designed networks, and inefficient PT systems. Incidents such as crashes and roadworks compound the problem, causing significant delays and forcing diversions. Inefficient traffic management, including poorly timed signals and lack of real-time information, also add to the congestion issues. Moreover, population growth and urbanization escalate the number of vehicles on the road, intensifying congestion when infrastructure fails to keep pace.

Addressing the highlighted congestion issues requires comprehensive planning, investment in infrastructure and technologies, and improved public transit systems. Long-term solutions also require coordination between various stakeholders and a combination of strategies tailored to the specific needs of each congestion mitigation area.

This chapter presents a comprehensive congestion reduction roadmap and resource guide, designed to address traffic congestion effectively by considering its causes and the size of the metropolitan population. The roadmap provides a clear vision and practical approaches for stakeholders involved in congestion mitigation, including managers, practitioners, and professionals in the field, as well as researchers and students. It serves as a valuable decision-making tool for developing congestion reduction strategies, prioritizing infrastructure and technology investments, and shaping improved policies. The project team recommends the following steps for utilizing the roadmap:

- **Identify Key Challenges:** Analyze specific congestion issues within the metro area, pinpointing critical locations, patterns, and causes. Explore targeted strategies and innovative solutions to effectively mitigate these challenges.
- **Leverage Best Practices:** Study successful congestion mitigation strategies implemented in metro areas of comparable size. Identify adaptable approaches and tailor them to meet the unique needs of the region.
- **Plan for Future Growth:** Forecast the metro area's development over the next 5 to 20 years, considering factors such as population growth and urban expansion. For instance, if transitioning from a medium to a large metropolitan area in the next decade, proactively plan and invest in systems, strategies, and infrastructure—both digital and physical—that have proven effective in larger regions.

The roadmap features 12 proven and emerging congestion mitigation strategies, each tailored to the unique needs of small, medium, large, and very large metropolitan areas. These strategies were developed through an extensive literature review and in-depth interviews with industry experts. Before delving into the core components and usage of the roadmap, key terms and classifications are introduced, including recurring and non-recurring congestion, roadway types, and the defining characteristics of various metro area sizes.

Description of Terms

Recurring Congestion

Recurring traffic congestion manifests as predictable patterns during specific times, notably during morning and evening commutes. It arises from several key factors, including:

- Synchronization of work and school schedules, which results in concentrated traffic volumes during rush hours.
- Bottlenecks that emerge at critical points like highway ramps and intersections, where merging and reduced lanes impede traffic flow and vehicles struggle to navigate through limited space.
- Inefficient traffic management practices, such as poorly timed signals and lane configurations that disrupt the flow of vehicles leading to frequent stops and inconsistent speeds.
- Lack of viable alternative routes that compound congestion, particularly when limited road options funnel traffic towards specific destinations.

Addressing recurring congestion necessitates strategic interventions targeting these root causes, including improved traffic management, TSM&O strategy implementations, needed infrastructure enhancements, and the promotion of alternative transportation methods to alleviate pressure during peak hours. Strategies for managing recurring congestion include optimizing traffic signal timings, implementing TSM&O strategies, applying transportation demand management measures, improving infrastructure, and promoting alternative modes of transportation (Mazzenga & Demetsky, 2009). Encouraging flexible work hours and telecommuting options can also help distribute traffic more evenly throughout the day.

Non-recurring Traffic Congestion

Non-recurring traffic congestion occurs irregularly due to various incidents and events, including:

- Traffic incidents like crashes or vehicle breakdowns that disrupt normal traffic flow by blocking lanes or partially closing roads until the situation is resolved.
- Planned and unplanned road works such as construction or maintenance activities that lead to temporary congestion through lane closures and reduced capacity.
- Large-scale special events such as sports games or concerts that attract a surge of vehicles, often causing congestion near the event venue due to limited parking and road closures.
- Severe weather conditions like heavy rain or snowstorms that impact road conditions and visibility, necessitating reduced speeds and road closures for safety.

These non-recurring congestion sources highlight the unpredictability of the issues, necessitating adaptive strategies to manage and mitigate their impacts effectively. Researchers have cited several strategies to manage non-recurring congestion (Farrag, Outay, Yasar, & El-Hansali, 2020; Judycki & Robinson, 1992). Among those include timely incident management (e.g., quick response to accidents or breakdowns), effective communication of road closures, and sharing of real-time traffic information. Proper planning and coordination between construction projects and road authorities can also minimize disruptions caused by road works.

Combining various strategies, such as traffic monitoring and management, implementation of TSM&O strategies, infrastructure investment improvements, alternative transportation options, and intelligent transportation systems can help address both recurring and non-recurring traffic congestion and enhance the efficiency and reliability of transportation networks (Concas, Kamrani, & Kummetha, 2021).

Congestion on Different Roadway Types

Traffic congestion issues may vary depending on the roadway type. Below is a breakdown of congestion problems by roadway type.

Interstates, Freeways, Expressways

Traffic congestion is a significant challenge on freeways and expressways within urban areas, despite being designed to facilitate high volumes of traffic and faster travel compared to local roads. Several factors contribute to congestion on these roadways (Hsu & Zhang, 2014), such as:

- High traffic volume, particularly during peak commuting hours.
- Commuters travel to and from work, the influx of vehicles taxes the infrastructure (Duranton & Turner, 2011).
- Bottlenecks at interchanges, ramps, and merging points that disrupt the flow of traffic, causing slowdowns as vehicles navigate these congested areas.
- Inadequate lane capacity that exacerbates the issue, especially during periods of heightened traffic demand.
- Incidents such as crashes or breakdowns further compound congestion by blocking or reducing lanes, impeding traffic flow until the situation is resolved. The time required to clear such incidents prolongs congestion.
- Additionally, poorly designed interchanges, merging lanes, and exit ramps contribute to congestion by impeding efficient traffic flow at critical junctions.
- Inefficient traffic management practices exacerbate congestion by hindering smooth traffic flow and causing delays (Bertini, 2005).
- Moreover, freeway construction, maintenance, and repair work can temporarily reduce lane capacity, leading to congestion as traffic is diverted or slowed down around work zones. Inefficient management of detours and diversions exacerbates congestion during these periods.

Overall, addressing freeway congestion necessitates a multi-faceted approach, blending short-term interventions with long-term solutions. A key aspect involves the implementation of advanced Traffic Management Systems (TMS), and leveraging Intelligent Transportation Systems (ITS). These systems enable real-time traffic monitoring, utilize variable message signs, and employ ramp metering. These strategies can help optimize traffic flow and enable prompt responses to incidents, bolstering freeway efficiency and reliability (Scott, 2002). Efficient Incident Management is critical for minimizing congestion. Swift response and coordinated efforts among emergency services, tow truck operators, and transportation authorities are pivotal in clearing incidents promptly, thereby mitigating congestion's impact. Needed infrastructure expansion also plays a role in alleviating freeway congestion. When there are no other better cost-effective options, increasing freeway capacity through lane additions, interchange improvements, and auxiliary lane construction addresses bottlenecks and chokepoints, enhancing traffic flow (Papageorgiou, Diakaki, Dinopoulou, Kotsialos, & Wang, 2003).

Promotion of PT and ride sharing offers an avenue to reduce individual vehicle usage on freeways, thereby easing congestion. Encouraging these alternative modes of travel contributes to a more balanced traffic distribution. Effective traffic demand management strategies, including flexible work hours, telecommuting incentives, and congestion pricing, help regulate traffic demand, promoting smoother flow and reducing peak-hour congestion. Lastly, meticulous construction planning and communication are essential to minimize disruptions caused by construction activities (Hyari, El-Mashaleh, & Rababeh, 2015). Coordinated scheduling, provision of alternative routes, and timely communication with drivers mitigate congestion resulting from construction and maintenance work. In conclusion, tackling freeway congestion mandates a comprehensive strategy, integrating infrastructure enhancements, optimized traffic management, alternative transportation promotion, and efficient incident response mechanisms.

Major and Minor Arterials

Traffic congestion is a prevalent issue on arterial roadways that connect various areas within urban settings. These thoroughfares, crucial for both local and through traffic, grapple with several contributing factors to congestion (Rao & Rao, 2016).

- High traffic volumes characterize arterials, particularly during peak commuting hours, exacerbating congestion as vehicle numbers surpass road capacity (Gartner & Stamatiadis, 2002).
- Inadequate signal timing and a lack of synchronization between traffic lights further compound congestion, fostering stop-and-go traffic patterns at intersections and causing delays.
- Insufficient lane capacity presents a significant challenge, especially when arterials lack adequate lanes to accommodate traffic volume.
- Lack of dedicated turning lanes exacerbate congestion, hindering the smooth flow of vehicles.
- The presence of on-street parking and loading activities along arterials poses another obstacle, disrupting traffic flow as vehicles stop or slow down for parking or loading/unloading goods, leading to congestion.
- Bus stops along these routes can contribute to congestion, particularly if inefficiently designed or lacking proper bus bays, leading to interruptions in traffic flow as buses pick up or drop off passengers (Boarnet, Kim, & Parkany, 1998).
- Heavy turning movements, such as vehicles making left turns at intersections or entering/exiting driveways, further impede traffic flow on arterials. Congestion ensues when turning vehicles obstruct through lanes or when turning capacity is inadequate.
- Insufficient infrastructure for pedestrians and cyclists, such as inadequate sidewalks or bike lanes, exacerbates congestion as these users interact with vehicular traffic (Cieśla, 2021).

Addressing congestion on arterials also necessitates a multifaceted approach, encompassing improved signal coordination, enhanced lane capacity, efficient parking management, optimized transit operations, and enhanced infrastructure for non-motorized modes of transportation. Addressing congestion on arterials entails the implementation of various strategies to improve traffic flow and reduce bottlenecks (Sakhrani & Chowdhury, 2016). Optimizing traffic signal timings and coordinating signals along these roadways can mitigate congestion by responding to real-time traffic conditions (Tsubota, Bhaskar, Chung, & Billot, 2011). Intersection improvements, such as dedicated turning lanes or roundabouts, enhance traffic flow, particularly during peak hours. Prioritizing bus operations through measures like dedicated lanes or transit signal priority helps streamline transit services, reducing congestion caused by buses (P. Anderson & Geroliminis, 2020). Moreover, enhancing pedestrian and bicycle infrastructure promotes safer active transportation options, minimizing conflicts with vehicular traffic. Efficient management of parking and loading activities along arterials, including designated zones and time restrictions, also contributes to congestion reduction. Additionally, integrating land use planning strategies that encourage mixed-use development to reduce urban sprawl can curtail the need for extensive trips, thereby alleviating traffic demand on arterials. By implementing a combination of these strategies, traffic congestion on arterials can be effectively managed, improving the flow of traffic and enhancing the overall transportation experience in urban areas.

Rural Roads

Traffic congestion on rural roads, though less frequent than in urban areas, stems from various factors such as seasonal tourism, agricultural activities, and school bus operations. Limited passing opportunities exacerbate congestion caused by slow-moving vehicles like tractors and trucks. Additionally, roadwork, incidents, diverted traffic due to a freeway crash, and inadequate traffic signal timing, can further impede flow.

To summarize, traffic congestion on rural roads can occur due to various factors despite lower traffic volumes and fewer lanes:

- Seasonal or tourist traffic during peak vacation periods overwhelms road capacity.
- Agricultural and commercial activities, with slow-moving vehicles like tractors and trucks, impede traffic flow.
- Heavy diverted traffic due to a major freeway crash.
- Inadequate traffic signal timing.
- School buses during drop-off and pick-up times add to congestion, exacerbated by reduced speed limits in school zones.

Addressing rural congestion requires tailored strategies, including adding passing lanes, adequate traffic signal timing at rural signalized intersections, special traffic signal timing to quickly respond to unexpected heavy traffic volumes, and improving signage for better driver awareness. Implementing ITS, such as dynamic message signs, aids in managing flow through real-time updates and alternative routes. Coordination of road maintenance and education campaigns on vehicle presence is vital. Identifying critical sections and upgrading infrastructure enhance traffic flow. By addressing these challenges, rural congestion can be effectively managed, albeit at a lower intensity than urban areas.

Effective Strategies by Roadway Types

The literature review and interview sections provided insights into how various congestion reduction strategies can help reduce congestion on different roadway types. The project team conducted further analysis and determined the congestion mitigation areas that are pertinent to various roadway types, as shown in Table 5.

Table 5. Effective Strategies by Roadway Types

Strategies	Interstates Freeways Expressways	Major and Minor Arterials and Collectors	Rural Roads
1. Smart and Advanced Signal Timing and Optimization Systems		✓	✓
2. Traffic Incident Management	✓	✓	✓
3. TSM&O Strategies	✓	✓	✓
4. Multimodal Transportation	✓	✓	
5. Shared Transport Systems	✓	✓	
6. Telecommuting and Flexible Work Hours	✓	✓	
7. Smart Navigation Systems	✓	✓	
8. Public Transportation Systems	✓	✓	
9. Congestion and Road Pricing	✓		
10. Connected and Automated Vehicles	✓	✓	✓
11. Advanced and Future Transportation Technologies	✓	✓	
12. Other Emerging Technologies	✓	✓	

Characteristics of Urban Areas and Common Transportation Infrastructure

As mentioned previously, traffic congestion varies by area type. To consider those variations, the project team used the four metropolitan categories described in the popular Texas Transportation Institute (TTI) Mobility Report (Schrank, Albert, Eisele, & Lomax, 2021). The four categories include:

- Very Large Urban Areas—over 3 million population
- Large Urban Areas—over 1 million and less than 3 million population
- Medium Urban Areas—over 500,000 and less than 1 million population
- Small Urban Areas—less than 500,000 population

These areas have different characteristics and transportation infrastructure that support the population residing in them. The characteristics and transportation infrastructure for each area size are explained next.

Very Large Urban Areas (Over 3 million population)

- **Characteristics**: Very large urban areas are densely populated with a significant concentration of people and resources. They are typically home to major economic and cultural centers with a wide range of industries, services, and amenities. These areas often have diverse and vibrant communities, extensive infrastructure networks, and high-rise buildings.
- **Transportation Infrastructure**: Very large urban areas have extensive transportation infrastructures to cater to the large population and high travel demand. They usually feature well-developed road networks, multiple expressways, and highways connecting different parts of the city. PT systems are highly developed, including metro/subway systems, commuter trains, and bus networks. These areas may also have major airports, seaports, and rail terminals for regional and international transportation.

Large Urban Areas (Over 1 million and less than 3 million population)

- **Characteristics**: Large urban areas are significant cities with a sizable population and a range of economic and cultural activities. While they may not be as densely populated as very large urban areas, they still offer a diverse and urbanized environment with various amenities and opportunities.
- **Transportation Infrastructure**: Large urban areas generally have a well-connected transportation network. They feature multiple highways and arterial roads to facilitate commuting within the city and connect to neighboring areas. Public transportation options are often available, including bus systems, light rail, or tram networks, and possibly a limited subway or metro system. Airports and seaports may be present, although they may not be as large or busy as those in very large urban areas.

Medium Urban Areas (Over 500,000 and less than 1 million population)

- **Characteristics**: Medium urban areas are smaller than large urban areas but still offer significant urban amenities and opportunities. They are often regional economic centers and may have a mix of urban and suburban areas.
- **Transportation Infrastructure**: Medium urban areas typically have a well-developed road network, including major highways and arterial roads. PT options can include bus systems, light rail, or commuter trains connecting different parts of the city and nearby regions. Airports may exist but might be smaller and serve domestic or regional flights.

Small Urban Areas (Less than 500,000 population)

- **Characteristics**: Small urban areas are relatively smaller in terms of population and physical size. They often have a mix of urban and suburban characteristics and may be centers for local commerce.
- **Transportation Infrastructures and Systems**: Small urban areas generally have a more limited transportation infrastructure compared to larger urban areas. They typically have a network of local roads and streets to facilitate local commuting. PT options may include bus systems or smaller-scale transit services. In some cases, small urban areas may not have dedicated PT systems, and reliance on private vehicles or other forms of individual transportation may be more prevalent.

Common Trends and Findings

While there are variations among these urban areas, several common trends and findings emerge (Fields, 2014; Louf & Barthelemy, 2014; Rahman, Najaf, Fields, & Thill, 2022):

- **Congestion Levels:** Congestion is more pronounced in very large and large urban areas than in medium and small urban areas due to higher traffic volumes. This leads to longer travel times and delays, particularly during peak hours in very large and large urban areas compared to medium and small urban areas.
- **Travel Time Delay**: Travel time delays are significant in very large and large urban areas, where commuters experience considerable delays due to congestion. Medium and small urban areas generally have lower travel time delays in comparison.
- **Vehicle Miles Traveled (VMT)**: Vehicle miles traveled are typically higher in very large and large urban areas due to population density and higher travel demand. Medium and small urban areas have comparatively lower VMT, indicating relatively lower levels of overall travel.

- **Public Transportation**: PT plays a crucial role in mitigating congestion in very large and large urban areas. These urban areas tend to have more extensive public transit systems. Medium and small urban areas may have smaller scale transit networks.
- **Traffic Signal Timing Strategies:** For small and medium urban areas, traffic signal timing and coordinated signal systems are particularly effective in improving traffic flow. While these strategies are also valuable in large and very large urban areas, their impact is limited in scenarios where traffic volumes approach or exceed roadway capacities.
- **Various Strategies for Congestion Mitigation**: Various strategies are implemented in urban areas to mitigate traffic congestion, with their effectiveness varying by urban size and traffic volume. TSM&O strategies and traffic incident management are critical for all urban areas, enhancing efficiency and reliability. Multimodal and shared transportation systems benefit cities of all sizes, with a particularly significant impact on large and very large urban areas. Strategies such as telecommuting and flexible work hours can substantially reduce congestion in large and very large urban areas by managing peak-hour demand. Congestion and road pricing could be effective for a very large metro area.
- **Alternative Transportation Modes:** Promoting alternative transportation modes like cycling and walking, supported by appropriate infrastructure, is essential for large and very large urban areas to encourage sustainable and efficient mobility.
- **CAVs, Advanced and Emerging Technologies**: Urban areas of all sizes will benefit from CAVs, advanced technologies, and emerging technologies in the future in terms of safety and mobility. They have the potential to influence travel patterns and reduce congestion.

Congestion Reduction Roadmap

As a result of the literature review and interviews, each of the 12 strategies considered in this report can help reduce congestion in different ways. In addition to the 12 congestion reduction areas, the project team added two other areas highlighted in the literature review and interviews: 1) New Roadway construction or Capacity Expansion, and 2) Land Use Policies, Other Policies, and Programs. After adding the two areas, 14 areas were considered overall in this section. The effectiveness of the 14 congestion reduction areas varies based on metropolitan area size and, for some, based on a timeline. This section provides the congestion reduction roadmap, notably, it pinpoints the strategies that are most helpful depending on the metro area sizes and timeline. For the urban area sizes, the project team used the metropolitan area classification in the TTI report described previously, including (see 4.1 for more details):

- Very Large Metropolitan Areas
- Large Metropolitan Areas
- Medium Metropolitan Areas
- Small Metropolitan Areas

Metropolitan areas of varying sizes have distinct transportation needs. To assess the effectiveness of 14 congestion mitigation strategies across small, medium, large, and very large metropolitan areas, the project team utilized insights from a thorough literature review, expert interviews, and real-world success stories. It is worth noting that the ratings assigned to small metropolitan areas can also be applied to rural settings. The effectiveness levels of these 14 strategies, categorized by metropolitan area size, are summarized in Table 6. These ratings were derived through qualitative methods conducted by the authors. However, due to time constraints, interview participants did not directly contribute to the rating process. Furthermore, since each interview participant specialized in specific areas of expertise, their input did not encompass all strategies under consideration.

The findings from the qualitative process reveal the following:

- PT systems, TSM&O strategies, incident management, and multimodal transportation are crucial congestion mitigation areas for very large and large urban areas. Additionally, congestion and road pricing are more important for very large areas than the other areas. Telecommuting and flexible hours and shared transportation can help alleviate congestion in very large and large areas by providing flexibility, more options, and reduce single vehicle occupancy.
- Smart and advanced signal timing and optimization systems are critical for small and medium metropolitan areas compared to large and very large urban areas.
- Incident management, TSM&O strategies, and land use are important for all area types.
- Major roadway construction or capacity expansion is an option that is discouraged for all metropolitan area sizes or should not be the first choice to consider in any area.
- Major roadway construction or capacity expansion should be avoided in case they are necessary. This approach is generally discouraged across all metropolitan area sizes and should not be considered as the primary solution without exploring other solutions. Alternative strategies that enhance efficiency and sustainability are typically more effective and cost-efficient.

Most of the congestion mitigation areas that are based on smart navigation systems, CAVs, advanced technologies, and emerging technologies have low or unknown effectiveness across metropolitan area sizes at the present time. Those areas are anticipated to evolve in the future (Table 7). Some notes related to each congestion mitigation area are as follows:

- **Smart and Advanced Signal Timing and Optimization Systems**: Although signal systems are very important, they are not the key solution for oversaturation in very large areas. However, good signal timing is important to reduce congestion in small urban areas.
- **Traffic Incident Management**: This strategy is important for all area types because it can help avoid congestion. It may be more crucial for very large areas.
- **TSM&O Strategies**: These strategies are currently useful for reducing congestion and will continue to be useful in the medium term and long term as technologies evolve.
- **Multimodal Transportation:** This congestion reduction area is an important complement to PT systems and for first- and last-mile trips.
- **Shared Transport Systems**: This area is an important complement to PT systems. The effectiveness level may be medium compared to other areas.
- **Telecommuting and Flexible Work Hours**: This congestion reduction area can help reduce the number of trips, which is even more important for very large and large areas.
- **Smart Navigation Systems**: Although they are important now, their full potential for reducing congestion is anticipated in the future.
- **Public Transportation Systems**: Are needed for very high-density areas and areas with high ridership.
- **Congestion and Road Pricing**: This is an important strategy to reduce congestion in very high-density areas.
- **CAVs**: Are anticipated to be effective long term for non-recurring congestion when fully adopted with high penetration rates but may induce more recurring congestion in the future.

- **Advanced and Future Transportation Technologies**: As technologies evolve, this area may become increasingly effective at reducing congestion.
- **Other Emerging Technologies**: As technologies evolve, this area may become increasingly effective in reducing congestion.
- **New Roadway Construction or Capacity Expansion**: This area is effective for a good period of time, but it may be costly and require time. This often leads to more congestion in the future.
- **Land Use Policies, Other Policies, and Programs**: Land use and policies are important for reducing congestion but may require time and effort to be established. If applied, the effects could be seen in the medium to long-term future.

Table 6. Congestion Reduction Area Effectiveness Levels by Metropolitan Area Sizes

Effectiveness Level of Congestion Reduction Strategy:	1	Low		
	2	Medium		
	3	High		
Congestion Reduction Strategy	**Metropolitan Area Sizes**			
	Small	Medium	Large	Very Large
Smart and Advanced Signal Timing and Optimization Systems	3	2	1	1
Traffic Incident Management	3	3	3	3
TSM&O Strategies	2	3	3	3
Multimodal Transportation	2	3	3	3
Shared Transport Systems	1	1	2	2
Telecommuting and Flexible Work Hours	1	1	2	2
Smart Navigation Systems	1	1	1	1
Public Transportation Systems	1	2	3	3
Congestion and Road Pricing	1	2	2	3
Connected and Automated Vehicles	1	1	1	1
Advanced and Future Transportation Technologies	1	1	1	1
Other Emerging Technologies	1	1	1	1
New Roadway Construction/Capacity Expansion	2	2	2	2
Land Use Policies, Other Policies, and Programs	2	2	3	3

These are now presented as a visual below to better understand which specific congestion mitigation area has a higher effectiveness for a particular metro area size. First, the very large area category is shown followed by the large, medium, and finally small urban area categories, as shown in Figure 32, Figure 33, Figure 34, and Figure 35, respectively.

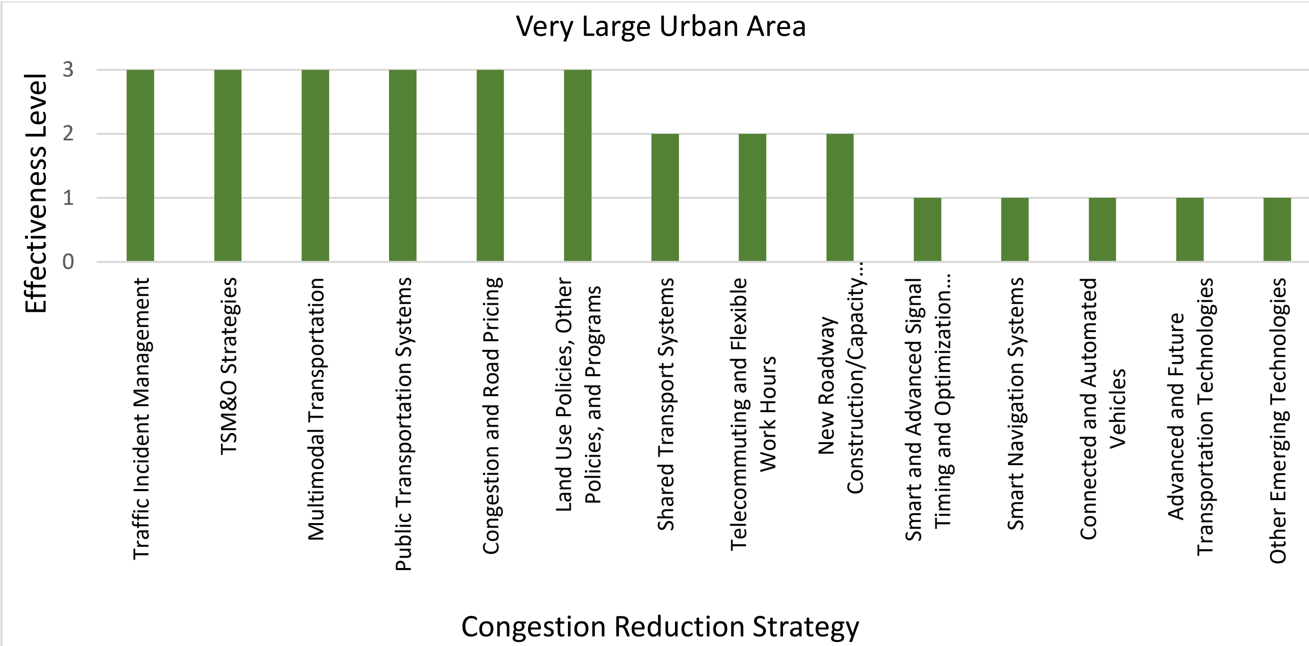


Figure 32. Very Large Urban Area – Effective congestion mitigation strategies.

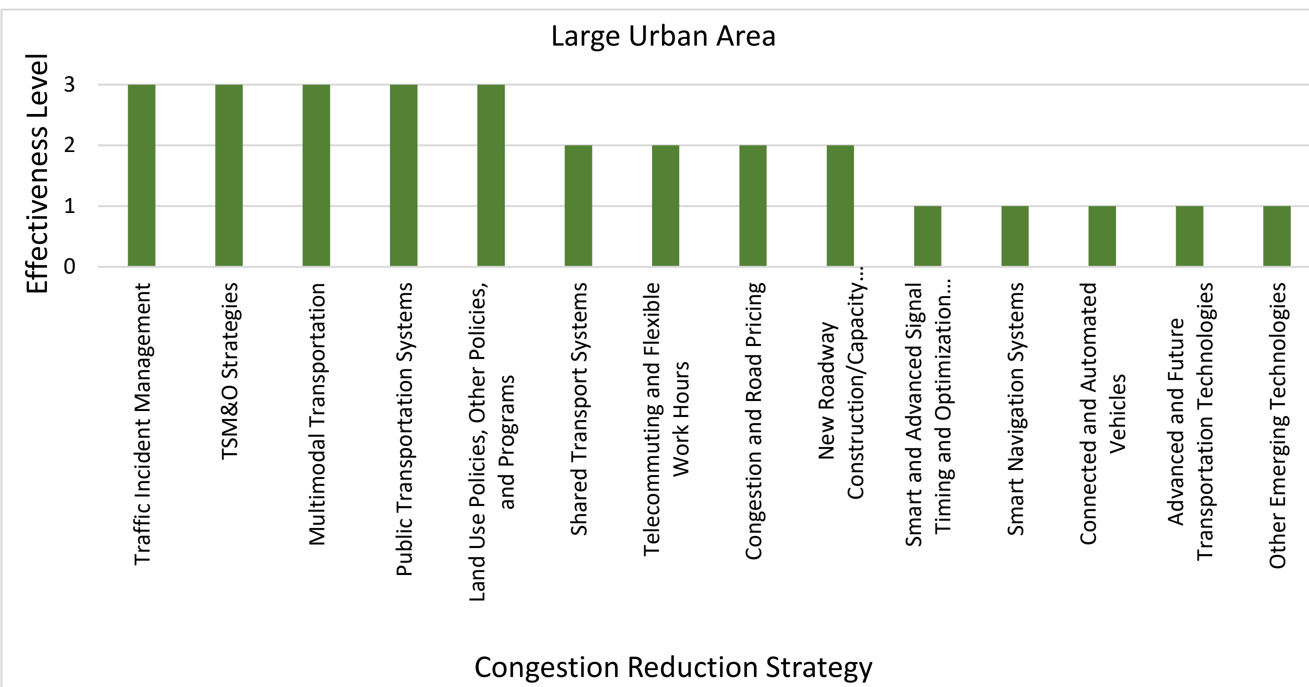


Figure 33. Large Urban Area – Effective congestion mitigation strategies.

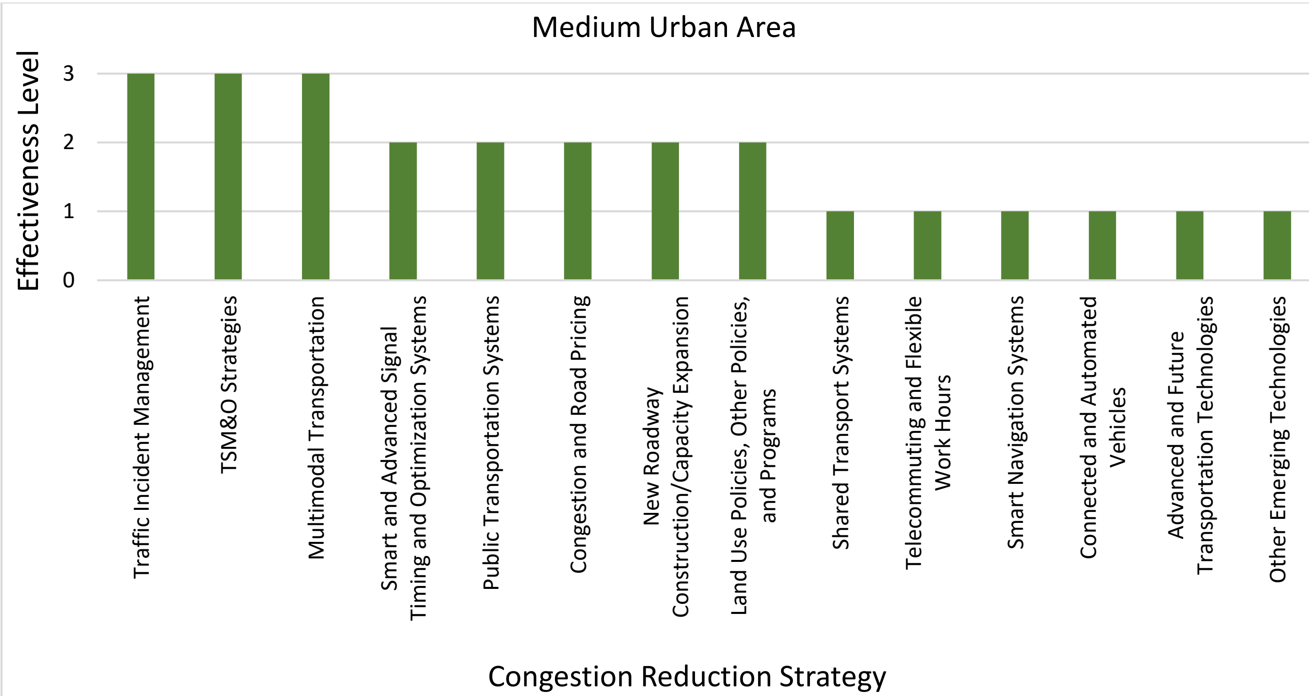


Figure 34. Medium Urban Area – Effective congestion mitigation strategies.

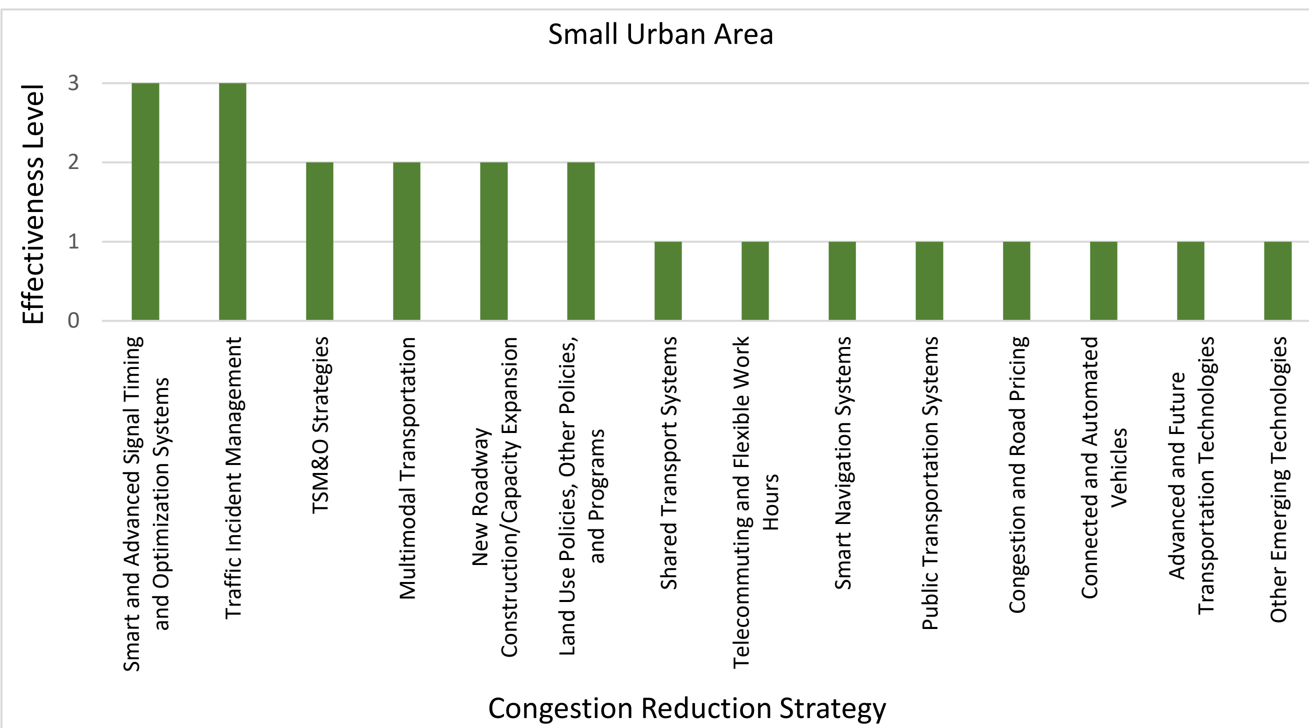


Figure 35. Small Urban Area – Effective congestion mitigation strategies.

Table 7. Congestion Reduction Area Effectiveness Levels by Timeline

Congestion Mitigation Areas	Timeline		
	Short-Term	Mid-Term	Long-Term
Connected and Automated Vehicles	1	2	3
Smart Navigation Systems	1	2	3
Advanced and Future Transportation Technologies	1	2	3
Other Emerging Technologies	1	2	3
Other: Land Use Policies, Other Policies, and Programs *(e.g., Smart growth policies, Car Free Zones, Urban growth boundaries, parking management policies)*	2	3	3

To account for advancements in technology, the project team separately evaluated congestion mitigation strategies related to smart navigation systems, CAVs, and other advanced and emerging technologies. The full potential of these strategies for mitigating congestion is expected to materialize in the long term, with less pronounced benefits in the medium and short term. Using the same rating framework as Table 6, the project team assessed these strategies based on their anticipated timeline, as shown in Table 7.

For instance, while CAVs currently demonstrate clear benefits for addressing non-recurring congestion, their long-term effectiveness is expected to increase as the technology matures with a high penetration rate in the field. Regarding recurring congestion, the literature discusses both the potential benefits and limitations of CAVs, with uncertainty about whether the advantages will ultimately outweigh the challenges. Similarly, smart navigation systems and other advanced technologies are projected to deliver greater benefits as they continue to evolve.

In addition to these technology-driven strategies, the team also evaluated the impact of land use and other policies over time. Well-designed land use policies are expected to significantly reduce congestion, particularly in the medium and long term. These insights underscore the importance of aligning technological and policy innovations with strategic planning to address congestion effectively across different time horizons.

Relationships Between Congestion Reduction Areas

Some strategies enhance or complement each other in congestion mitigation efforts. For example, shared and multimodal transportation systems complement PT by addressing first- and last-mile connectivity and incident management helps by providing efficient and effective responses to unexpected events or disruptions, ensuring the continued operation and reliability of public transit systems. Table 8 depicts the relationships between the 12 congestion mitigation areas and subareas.

Table 8. Relationships Between Congestion Reduction Strategies

	Smart and Advanced Signal Timing & Optimization Systems	Traffic Incident Management	Transportation System Management and Operations	Multimodal Transportation	Shared Transportation Systems	Telecommuting and Flexible Work Hours	Smart Navigation Systems	Public Transportation Systems	Congestion and Road Pricing	Connected and Automated Vehicles	Advanced and Future Transportation Technologies	Other Emerging Technologies
Smart and Advanced Signal Timing & Optimization Systems			✓							✓		
Traffic Incident Management			✓			✓	✓				✓	✓
Transportation System Management and Operations	✓	✓							✓	✓		
Multimodal Transportation					✓	✓		✓			✓	✓
Shared Transportation Systems				✓		✓		✓			✓	✓
Telecommuting and Flexible Work Hours		✓		✓	✓							
Smart Navigation Systems		✓						✓	✓	✓	✓	✓
Public Transportation Systems				✓	✓		✓		✓			✓
Congestion and Road Pricing			✓				✓	✓		✓		
Connected and Automated Vehicles	✓		✓				✓		✓			✓
Advanced and Future Transportation Technologies		✓		✓	✓		✓					
Other Emerging Technologies		✓		✓	✓		✓	✓		✓		

Successful Implementations in Congestion Reduction Areas

There are various implementations, deployments, and pilot projects focused on the 12 congestion mitigation areas in this report. However, it should be noted that the ones related to technologies have limited examples due to their newness. This section provides examples of implementations, deployments, or pilot projects for each area. The urban areas with successful implementations in each congestion mitigation area are shown in Table 9 and more details on the implementations are provided in the summary provided below.

Table 9. Successful Implementations in Congestion Reduction Areas

Areas	Very Large Urban Area	Large Urban Area	Medium Urban Area	Small Urban Area	Other (Statewide/ Nationwide)
Smart and Advanced Signal Timing & Optimization Systems	Los Angeles, CA; Dallas, TX; San Diego, CA	Pittsburg, PA; Copenhagen, Denmark	Sarasota-Bradenton, FL	Pasadena, CA; Gainesville, Deland, Panama City, Bartow, FL; Dubuque, IA	Colorado; Minnesota
Traffic Incident Management	Maryland (Washington, Baltimore, Annapolis, and Frederick);	Nashville, TN	Sarasota-Manatee County, FL		Florida
Transportation System Management and Operations	San Diego; Dallas, Houston, TX	Austin, TX; Richmond, VA; Orlando, FL			Arizona; Virginia; Oregon; Maryland; Texas; Florida
Multimodal Transportation	San Francisco, CA; Dubai, UAE	Denver, CO	Portland, OR		
Shared Transportation Systems	New York, NY; Miami, FL; Washington DC; Seattle, WA; Boston, MA; Chicago, IL				USA, Canada, UK, Spain, Germany, France, Belgium
Telecommuting and Flexible Work Hours	Seattle, WA; San Francisco, CA; Washington DC	Austin, TX	Portland, OR		Minnesota

Table 10. Successful Implementations in Congestion Reduction Areas (Continued)

Areas	Very Large Urban Area	Large Urban Area	Medium Urban Area	Small Urban Area	Other (Statewide/ nationwide)
Smart Navigation Systems	San Francisco, CA	Minneapolis-St. Paul, MN-WI; St. Petersburg-Tampa, FL			
Public Transportation Systems	Los Angeles, CA; San Francisco, CA; Minneapolis, MN; Seattle, WA	Denver, CO; Cleveland, OH	Sarasota-Bradenton, FL	Oakland, CA; Richmond, VA; Manatee County, FL	
Congestion and Road Pricing	Seattle, WA; New York City, NY; San Francisco, CA; London, United Kingdom	Milan, Italy	Gothenburg, Stockholm, Sweden		
Connected and Automated Vehicles	New York City, NY	St. Petersburg-Tampa, FL; Columbus, OH; Phoenix, AZ; Orlando, FL	Gothenburg, Sweden	Ann Arbor, MI; Salt Lake City, UT	United Kingdom; Wyoming
Advanced Transportation Technologies		Charlotte, NC		Lockeford, CA; College Station, TX; Bowling Green, OH	
Emerging Technologies	Miami, Orlando, FL; Dallas, Houston, TX; Seattle, WA; Los Angeles, CA; Dallas, TX				

Smart and Advanced Signal Timing and Optimization Systems

Very Large Urban Areas

<u>Adaptive Signal Control Technology (ASCT) in Los Angeles, CA</u>

In Los Angeles, the Department of Transportation (LADOT) developed and deployed an Adaptive Traffic Control System (ATCS) from 1999 to 2001. The ATCS automatically adjusts traffic signal timing at 375 intersections. In March 2021, Los Angeles launched an automated traffic control system that synchronizes all 4,700 of the city's traffic lights (LADOT, 2023). The LADOT claims that their Automated Traffic Surveillance and Control (ATSAC) reduced travel time delays by 32 percent and emissions by three percent.

Traffic Management System in Dallas, TX, San Diego, CA, and Copenhagen, Denmark

In 2018, the city of Dallas partnered with Ericsson to improve the city's traffic management system. The updated system was able to adjust traffic signals across hundreds of intersections in real time and to connect to local transit systems. The upgraded system allows a bus rapid transit route to be prioritized through targeted greenlight timing (Citron, 2019). Several smart city projects (San Diego, Copenhagen) are using smart street lighting as a platform to integrate advanced traffic management and other applications.

Large Urban Areas

Scalable URban TRAffic Control (SURTRAC) in Pittsburg, PA

SURTRAC (Scalable URban TRAffic Control) is an innovative ATCS equipped with individual computers and software with AI capabilities developed in 2012 by the Robotics Institute at Carnegie Mellon University (CMU). "Surtrac uses a decentralized network of smart traffic lights equipped with radar, cameras, and other sensors to manage traffic flows. Surtrac's sensors identify approaching vehicles, calculate their speed and trajectory, and adjust a traffic signal's timing schedule as needed. A Surtrac-equipped intersection then distributes the timing and vehicle information it collects to other nearby 'smart' intersections, which can use that information, along with their own data, to adjust their own signals" (Austin, 2019).

Compared to the centralized ATCSs, "each signal in the SURTRAC system works independently and uses neighboring signals' data to determine its own schedule" (Salem et al., 2015). Thus, SURTAC enables traffic to be managed in real-time based on actual, not predicted, volume. SURTRAC was deployed on nine intersections in Pittsburgh. The assessment after implementation revealed a 25 percent reduction in travel time, 30 percent fewer stops, and 40 percent less time idling in traffic jams (Austin, 2019; Kiger, 2022; Salem et al., 2015). The system expanded to 50 intersections throughout Pittsburgh. The plan is to deploy it at between 150 and 200 intersections, about a third of the city's intersections (Austin, 2019).

Medium Urban Areas

Adaptive Signal Control Technology (ASCT) in Florida

The ASCT project aimed to optimize signal timings based on real-time traffic conditions. It used advanced algorithms to adjust signal timings dynamically and reduce delays along congested corridors. ASCT utilizes data from various sources, including traffic sensors, cameras, and communication networks, to continuously monitor traffic conditions at intersections. It then adjusts signal timings dynamically to improve traffic flow, reduce delays, and enhance overall intersection efficiency. Performance metrics for this project included Delay at Intersections, Queue Length (at critical intersections), Queue to Lane Storage Ratio (at critical intersections), and Passenger Car Equivalent (PCE) flows (at critical intersections). The ASCT implementation resulted in reduced travel times, improved intersection throughput, and decreased stops (Elefteriadou et al., 2019).

In Florida, the ASCT was deployed on Newberry Road (Gainesville), US 17/92 (Deland), Beach Parkway and 23rd Street (Panama City), University Parkway (Sarasota), 66th Street (St. Petersburg), SR 70 (Bradenton), and E. Van Fleet Drive & N. Broadway Ave. (Bartow) (Elefteriadou et al., 2019). It was found that the ASCT increased throughput by 6.96 percent and reduced queues by 15.57 percent. However, it was noted that the ASCT benefitted major streets most while the queues increased by 16.98 percent on the minor streets.

Small Urban Areas

Smart Travel in Dubuque, IA

In Iowa, the city of Dubuque partnered with IBM to create a smart city initiative with a focus on "Smarter Travel." This collaboration led to the inception of the Smart Traffic Routing with Efficient & Effective Traffic System (STREETS) project in 2018 (Iowa, 2018). The aim of this project was to enhance mobility by reducing travel time and congestion, increasing throughput, and improving intersection operation and safety. Providing real-time road network information to travelers, including comparative travel times, construction updates, incident alerts, and historical data, accessible through various media channels for informed decision-making, were also key objectives of this project. The project was launched in 2020 with a proposed completion date of December 2023.

Other Examples

Colorado Department of Transportation (CDOT) deployed two ATCS applications (InSync and QuicTrac) in two regions in 2012. The implementations led to six percent to nine percent weekday travel time improvements ((Salem et al., 2015). Likewise, the Missouri Department of Transportation (Missouri DOT) conducted a before and after study of ATCS (InSync systems) installed at 12 intersections on a 2.5-mile section of route-291 in Lee's Summit, Missouri. The 2010 study showed that ATCS can improve travel time by 39 percent (Salem et al., 2015).

SMART Signal, created by researchers in Minnesota, has been installed at more than 30 intersections in Minnesota and six intersections in Pasadena, California. The system has decreased congestion and improved travel time for many corridors (ITS, 2012).

Traffic Incident Management

Very Large Urban Areas

Coordinated Highways Action Response Team (CHART) Traffic Incident Management, MD

Emergency Traffic Patrols (ETPs) and Emergency Response Technicians (ERTs) have played a vital role in aiding motorists with disabled vehicles and managing incidents on Maryland's highways since the 1980s. CHART's mission is dedicated to enhancing the efficiency and safety of Maryland's primary highways by deploying Intelligent Transportation System (ITS) technology and fostering collaborative efforts among various agencies. The primary focus is on optimizing the transportation networks in Washington, Baltimore, Annapolis, and Frederick. CHART concentrates its efforts on about 375 miles of interstate bi-ways and 170 miles of state highway arterials within this specific geographic area. The CHART system enhances responder safety, facilitates the quick clearance of Maryland's travel lanes, enhances interagency communications, delivers real-time updates to travelers, and mitigates secondary crashes. All these efforts are directed toward ensuring the safety of motorists in Maryland.

CHART assisted motorists more than 37,400 a year, which means every 16 minutes. The team manages traffic at an incident once every 22 minutes, which contributes to the prevention of an estimated 225-250 secondary incidents each year. CHART's average response time is 7:36 seconds, and the average closure time is 29:31 minutes (Traffic Incident Management Newsletter, 2019).

Large Urban Areas

Nashville, TN

The I-440 Reconstruction Project was the largest in the Tennessee Department of Transportation (TDOT) history. During reconstruction, the route remained open to traffic except for a few select weekend closures. Recognizing the challenges posed by the planned lane and shoulder constraints, an incident management plan was developed. TDOT collaborated with various external partners, including Kiewit (the contractor), Nashville Police and the Highway Patrol, Nashville Public Works, Nashville OEM, Metro ECC, and Medcom (Vanderbilt Life Flight). The comprehensive plan ensured all stakeholders understood their roles in quickly clearing crashes and reopening the road.

The Incident Management Plan for I-440 was strategically developed to handle road incidents as quickly as possible due to the lack of shoulder area and heavier-than-normal congestion. This proactive plan significantly reduced incident clearance times, making the commute for area motorists better than it would have been without a plan.

Prompt road openings reduced nonrecurring delays on the routes and helped ensure travel time reliability for motorists. Additionally, the efficient handling of incidents on I-440 alleviated congestion on nearby routes, preventing traffic diversions and maintaining the balance of vehicular flow. This approach played a crucial role in preventing overwhelming traffic on adjacent surface streets, preserving the overall transportation efficiency in the project vicinity (National Operations Center of Excellence, 2020).

Medium Urban Areas

Route Diversion during Incidents in Sarasota, FL

In incident management, route diversion refers to the process of redirecting traffic away from a particular route or roadway due to an incident or disruption. This could be necessary in various situations, such as crashes, road closures, construction work, or other emergencies that render a route impassable or unsafe for travel. Route diversion aims to minimize congestion, ensure the safety of motorists and pedestrians, and maintain the flow of traffic by offering alternative routes or detours to bypass the affected area (Huaguo, 2008; Kou; Lin & Kou, 2003). Traffic simulation analysis indicates that properly adjusted signal timings on alternative routes significantly reduce travel times during freeway incidents, offering savings from 18 percent to 80 percent. Delaying traffic diversion and adjusting signals in peak hours minimizes network delay. Off-peak adjustments provide shorter freeway travel times without significant differences in alternative routes (Lin & Kou, 2003).

Other Examples

Florida ='s Road Ranger Program

Florida's Road Ranger Program deploys dedicated service patrols on major highways, effectively reducing incident durations and enhancing traffic flow. These skilled teams offer prompt assistance, clearing obstructions and providing services like tire changes and jump-starts. Trained in incident management, they collaborate with emergency responders, ensuring safety. Road Rangers also offer traffic control and valuable guidance to motorists, contributing to reduced congestion. The program's success hinges on collaborative partnerships with law enforcement, transportation departments, and emergency services.

The Road Ranger Program is continually evaluated to assess its effectiveness and identify areas for improvement (Salum, Sando, Alluri, & Kitali, 2020). There is research which evaluates the road ranger program and derives performance metrics to assess its effectiveness (Salum et al., 2020). It was found that incidents that involved road rangers resulted in a considerable decrease in incident clearance time. It was estimated to be at least 14 minutes less than other agencies. Overall, the Road Ranger program offers a 25.3 percent reduction in incident clearance duration while it is expected to reduce the incident clearance duration of crashes, vehicle problems, and traffic hazards by 23.2 percent, 32.1 percent, and 43.9 percent, respectively. It was also found that for minor, moderate, and severe incidents, Road Rangers' response is also expected to reduce incident clearance durations by 26.1 percent, 22.4 percent, and 15.8 percent, respectively (Salum et al., 2020).

Transportation System Management and Operations

Very Large Urban Areas

Integrated Corridor Management (ICM) in San Diego, CA, Dallas and Houston, TX

ICM is a comprehensive, team approach to battling congestion by coordinating within a corridor. The US Department of Transportation (US DOT) selected two corridors to demonstrate to the nation's ICM initiative: US 75 in Dallas, TX and I-15 in San Diego, CA (Petrella, Minnice, & Lappin, 2014). The primary goals of the I-15 ICM project were to enhance traffic flow, reduce congestion, improve traveler information, and provide a more reliable and efficient transportation system. The project utilized advanced technology and real-time data to achieve these objectives (Alexiadis, Chu, & Systematics, 2016; Miller & Skabardonis, 2010).

In San Diego, the implementation of ICM resulted in enhanced travel times, with peak period savings ranging from 250 to 1,300 person-hours. Travel time reliability also saw improvement, averaging 368 hours during southbound AM peak period activations and 569 hours during northbound PM peak period activations. Conversely, Dallas experienced marginal travel time improvements, with peak period person-hour savings ranging from six to 262 hours. In Dallas, travel time reliability saw a marginal average improvement of 109 hours during each northbound PM peak period ICM activation, while no improvement was observed in the southbound direction (FHWA, 2020a).

During a hurricane event, Houston successfully opened roadway shoulders in reversible lanes. An example of how TSM&O can be used for non-recurring congestion.

Large Urban Areas

Dynamic Queue Warning on I-35 in Austin, TX

One successful example of a TSM&O application happened in Austin, Texas, on I-35. Over the last five years, the 100-mile stretch of I-35 has been under reconstruction with a lot of different phases, and it is a heavily traveled corridor and one of the busiest interstates in the country. They have had a comprehensive management plan associated with all the construction and deployed a dynamic queue warning system that helped. Many traveler information technologies were deployed and used as part of that implementation: a website, text messages, new e-mail alerts, and a lot of ground management with property owners and businesses in those areas to try to provide information. It has been a successful and comprehensive approach to managing this huge congestion construction project or series of projects using TSM&O strategies.

Active Traffic Management (ATM) on I-66 in Richmond, Virginia

The I-66 ATM project implemented various TSM&O strategies, including variable speed limits, dynamic lane control, and real-time traveler information systems. The goal was to enhance traffic flow, reduce congestion, and improve safety. Performance metrics for this project included reduced travel times, improved reliability, and fewer incidents (Chun & Fontaine, 2016; Dutta, Boateng, & Fontaine, 2019). The variable speed limits adjusted in real-time enhance traffic flow and safety, while dynamic lane control optimizes lane use. Overhead signs and signals adapt lane assignments based on traffic conditions. Real-time traveler information, including dynamic signs and mobile apps, empowers drivers with up-to-date data to make informed decisions and avoid congestion.

The operational analysis revealed notable enhancements in travel time during off-peak hours following the activation of the ATM system. However, it indicated that travel time during peak periods in the primary direction of travel generally did not experience improvements. The majority of these improvements were concentrated on hard shoulder running (HSR) segments (Dutta, Fontaine, Boateng, & Campbell, 2018; Evaluation, 2018).

Orlando, FL

Seminole County in the Orlando area has implemented several dynamic lane assignments with success in using that strategy. Metroplan in Orlando, Florida, has a successful traffic signal retiming program.

Other Examples

Examples of successful implementations:

- An Arizona study on the effectiveness of traffic signal coordination concluded that crash rates on intersection approaches decreased by 6.7 percent after signal coordination.
- In Virginia, researchers found nearly a 25 percent reduction in total crashes of all severity levels on segments of I-66 where hard-shoulder running was deployed.
- Road weather information systems can reduce traveler delays and lower crash rates by 7 to 83 percent.
- In 2014, the Oregon DOT deployed an active traffic management system on OR 217 that included variable speed limits, traveler information, queue warning, and updated ramp metering. Preliminary crash data showed a 21 percent reduction in the total number of crashes after the first full year.
- Traffic incident management was successful in Maryland.
- A variable speed limit pilot study was conducted by the Texas Department of Transportation at three different locations in Texas. One dealt with recurrent congestion, another one had to do with weather, and the last one had to do with work zones. Some before and after data was obtained to analyze.
- FDOT implemented and operated managed lanes to reduce congestion and maximize throughput. In addition, FDOT and the Florida Highway Patrol have a 90-minute Open Roads Policy which encourages safe and efficient clearance of lane-blocking traffic incidents. As a result, most lane blockages are cleared within 60 minutes or less along Florida freeway and turnpike routes.
- For congestion due to incidents or for recurring congestion, dynamic message signs (DMS) provide real-time information to travelers in Florida approaching congestion and/or in case of traffic incidents. They allow drivers to slow down before the "hard brake" and possibly take alternative routes before they are impacted by the congestion. These strategies can also help reduce the occurrence of secondary crashes, which can be more severe than the initial incident.

Multimodal Transportation Systems

Very Large Urban Areas

San Francisco Bay Area's Transbay Transit Center

The Transbay Transit Center in San Francisco is a multimodal transportation hub that connects various modes of transportation including buses, trains, and future high-speed rail. By offering seamless connectivity between different modes, the transit center aims to reduce congestion in the Bay Area by encouraging the use of PT (Center, 2018).

Dubai's RTA Integrated Mobility Platform

Dubai's Roads and Transport Authority (RTA) has developed an Integrated Mobility Platform that integrates various transportation services including metro, tram, buses, water taxis, and ride-hailing services. This platform provides real-time information and seamless ticketing options for commuters (Banna, 2023). The RTA was also quoted as saying, "Dubai is planning to introduce integrated service centers with all of the necessary facilities that allow residents to reach their destinations within a 20-minute timeframe on foot or by bicycle" (Banna, 2023). An increase of 35 percent in public transport and multimodal transportation was reported by the RTA in 2022. This shows that with improved transit options riders are switching to PT and using different modes to commute.

Large Urban Areas

Denver Union Station (Denver, Colorado)

Denver Union Station is a multimodal transportation hub that serves as the central transit point for the Denver metropolitan area. It integrates various transportation modes, including light rail, commuter rail, buses, taxis, and bicycles. The station provides convenient transfers between different modes, making it easier for commuters to access the city and surrounding areas. The different modes of transportation are listed as follows (Perkins-Smith & Gibson, 1995; Wiener, 2005):

1. Light Rail
2. Commuter Rail
3. Amtrak
4. Bus Services
5. Bike Facilities
6. Pedestrian Connectivity
7. Public Plaza and Amenities

These different modes of transportation work cohesively to get the traveler from point A to point B. These modes are part of a broader initiative to improve mobility, enhance transit options, and create a more walkable and connected urban environment.

Medium Urban Areas

Portland's SmartPark Garages

In Portland, Oregon, SmartPark Garages are an example of multimodal transportation projects. These garages are strategically located near public transit hubs and offer bicycle parking facilities, electric vehicle charging stations, and car-sharing services, promoting the use of various transportation modes (Portland.gov, 2023). These facilities promote multimodal transportation and are expected to reduce congestion on Portland's roadways and bring in revenue.

Shared Transportation Systems

Very Large Urban Areas

Citi Bike (New York City, Miami); Capital Bikeshare (Washington D.C.)

Citi Bike is a bike-sharing program launched in New York City in 2013. It provides residents and visitors with access to a large fleet of bicycles stationed at various docking stations throughout the city. Citi Bike has been widely embraced and has played a significant role in promoting cycling as a viable transportation option in New York City (Kaufman, Gordon-Koven, Levenson, Moss, & Management, 2015; O'Mahony & Shmoys, 2015). Citi Bike in New York was successful in generating travel time savings of 5.78 hours and 8.19 hours in 2013 and 2015, respectively (Sobolevsky, Levitskaya, Chan, Postle, & Kontokosta, 2018).

Capital Bikeshare is one of the most successful bike-sharing programs in the U.S. It began operating in Washington, D.C. in 2010 and has expanded to include the surrounding metropolitan area. Capital Bikeshare offers thousands of bicycles at docking stations throughout the region, providing residents and tourists with a convenient and environmentally friendly transportation option (Wergin & Buehler, 2017). One study confirms that the presence of bikeshare stations approximately reduces traffic congestion by 4 percent (Hamilton & Wichman, 2018).

Seattle, WA

In a separate study, Fan and Harper delved into the potential implications on congestion, emissions, and energy consumption by examining the scenario where a portion of short car journeys is substituted with micromobility modes, such as bike-sharing systems. Seattle served as the focal point for their case study. Through their data analysis, they identified that around 48 percent of peak hour trips in Seattle fall within the short trip category (0-3 miles), and approximately 18 percent of these journeys have the potential to be replaced by micromobility modes. Their findings considered various factors, including the age of commuters, tour and trip purposes, time of day, and weather constraints, acknowledging that micromobility may not be a universal alternative for specific private car trips (Z. Fan & Harper, 2022)

In the same study, following the execution of traffic simulations, a comparison with their base case scenario (2014 base case) revealed a decrease of approximately 10 percent in severely congested road segments and an increase of one percent in non-congested road segments. The results of traffic simulations further indicate that the substitution of micromobility modes has a more pronounced positive impact on urban arterials compared to freeways or expressways. This discrepancy is attributed to the fact that short car trips, which are more prone to substitution by micromobility, predominantly occur on urban arterials rather than on freeways and highways (Z. Fan & Harper, 2022).

Micromobility in different very large urban areas of the U.S. and Canada

The five longest-running and most heavily used shared micromobility systems in the U.S. and Canada–BIXI (Montréal), Bluebikes (greater Boston), Capital Bikeshare (greater Washington D.C.), Citi Bike (NYC, Jersey City, and Hoboken), and Divvy (Chicago and Evanston)–have successfully operated as public-private partnerships (or in the case of BIXI, a city-run non-profit) for over a decade. Shifting priorities amongst private-sector operators, however, have raised questions about the durability of the current operating model of some systems (National Association of City Transportation Officials, 2022).

Other Examples

Zipcar Program Across the U.S.

Zipcar is a car-sharing service that operates in various cities across the U.S., Canada, and Europe. Some examples of cities are Tampa, Charlotte, Los Angeles, Chicago, Boston, Miami, etc., in the U.S., Toronto, Vancouver, Montreal, etc., in Canada, and London, UK, Barcelona, Spain, Berlin, and Germany to name a few. It allows members to rent vehicles on an hourly or daily basis, providing a cost-effective alternative to traditional car ownership. Zipcar has gained popularity in urban areas where owning a car may be impractical or expensive, promoting a more sustainable and flexible approach to transportation. Zipcar provides numerous benefits to its members and the communities it serves. It offers a cost-effective transportation option, as members only pay for the time they use the vehicle, without worrying about additional costs like insurance or maintenance. Zipcar also promotes sustainability by reducing the need for private car ownership and encouraging the use of shared resources, leading to reduced congestion and environmental impact.

As stated by Holmes (Holmes, 2015), Zipcar's mission is to "enable simple and responsible urban living," which has been guiding and driving the enterprise for the past 15 years. The Zipcar model enables people to have access to vehicles when in need and reduces their car ownership cost. It is a membership model, and users can subscribe to Zipcar using their mobile phones. Zipcars are strategically stationed near metro stations, train stations, universities, etc., to cover last-mile distances too. It is also noted that Zipcars have been able to reduce transportation total costs by 19 percent and subsequently decrease total vehicle miles traveled, thus reducing the number of vehicles on the road and hence reducing congestion, emission, and energy consumption. (Liu, Fagnant, & Zhang, 2016).

Telecommuting and Flexible Work Hours

Very Large Urban Areas

Trip Reduction Programs Across the U.S. (Seattle, San Francisco, Washington D.C)

Several cities and regions in the U.S. have implemented Commute Trip Reduction (CTR) programs to promote telecommuting and flexible work hours. These programs incentivize employers and employees to adopt alternative work arrangements, such as telework and flexible schedules, to reduce the number of single-occupancy vehicle trips during peak commuting hours. Several cities in the U.S. have implemented Commute Trip Reduction (CTR) programs to encourage alternative transportation options and reduce peak hour congestion. The performance metrics for these are drive-alone trips (DAR) and vehicle miles traveled (VMT) by employees. These programs aim to reduce both DAR and VMT.

Seattle has a long-standing and comprehensive CTR program called Commute Seattle. It focuses on reducing drive-alone commuting by promoting transit, walking, biking, and telework options. The program works with employers to develop transportation demand management strategies and provides resources, incentives, and support for alternative commuting options. The citywide drive-alone rate (DAR) decreased by nearly 10 percent, falling from 31.5 percent in 2017-2018 to 28.4 percent. The city surpassed the 2023-2024 DAR target of 28.8 percent, achieving 30.6 percent in 2019-2020. Eight out of 11 networks met their 2019-2020 DAR target. Citywide, VMT per employee dropped by 12.2 percent, from 4.5 percent in 2017-2018 to 3.9 percent in 2019-2020. The city surpassed the 2023-2024 target of 4.0 percent, achieving 4.3 percent in 2019-2020. Seven networks met their VMT per employee target, with four that didn't exceed their target by 0.1 or 0.2 (Seattle.gov, 2021).

The Bay Area Commuter Benefits Program in San Francisco, CA, is an initiative that requires employers with 50 or more full-time employees to offer commuter benefits, such as transit subsidies, vanpool programs, and telecommuting options. The program aims to reduce single-occupancy vehicle trips and promote sustainable commuting choices across the region. According to the True North survey, it is estimated that, because of the Program, employees in the Bay Area decreased their daily vehicle trips by 17,880 and monthly trips by 357,610. In the initial 12 months following the implementation of the regulation, the program led to a reduction of 4,291,300 vehicle trips and 85,600,000 miles of vehicle travel (Commission, 2016).

The District of Columbia's Transportation Demand Management (TDM) program in Washington, D.C., focuses on reducing traffic congestion and promoting sustainable transportation options. The program includes initiatives such as goDCgo, which provides information, resources, and incentives for residents and commuters to use alternatives to driving alone, including public transit, biking, walking, and carpooling. goDCgo facilitated travel changes for 33,500 individuals, resulting in the elimination of 33,260 daily vehicle trips and a reduction of 509,000 daily vehicle miles traveled (VMT) (Consulting, 2015).

Large Urban Areas

Trip Reduction Program in Austin, TX

The City of Austin's CTR and Leave Time Travel Incentive (LTR) program aims to reduce single-occupancy vehicle trips and promote alternative transportation options. It provides employers with resources, tools, and guidance to develop transportation demand management plans, including flexible work arrangements, transit subsidies, administrative leaves, and bike-friendly amenities. The mode split for Smart Commute Rewards participants shifted from 53 percent driving alone before the permanent program to 41 percent just six months later. Around 1 million vehicle miles were averted, equivalent to taking 61,000 vehicles off the road and reducing overall congestion (Tools of Change, 2021).

Medium Urban Areas

Trip Reduction Program in Portland, OR

Portland's CTR program, called Portland SmartTrips, aims to reduce traffic congestion and promote sustainable transportation choices. It provides personalized travel assistance to residents and employees, including information about transit options, carpooling, biking, and walking. The program also offers incentives and resources to encourage participation in alternative commuting. There was a reduction of 1,076,118 vehicle miles traveled (VMT), equivalent to 200 miles per target new resident per year. Among all new resident populations, not just those who ordered information and materials, there was a notable 10.4 percent decrease in drive-alone trips. Additionally, there was a relative increase of 13.6 percent in the use of environmentally-friendly modes among new residents (Tools of Change, 2013).

Other Examples

Minnesota

Minnesota is a national leader in telecommuting: The final element of the Minnesota Urban Partnership Agreement is telecommuting. This locally funded effort focused on expanding upon the successful Results-Only Work Environment (ROWE) program, where employers agree to evaluate employee results in lieu of requiring physical presence at the worksite at specific times and provide employees the flexibility to telecommute or shift their hours to avoid congested commutes. Approximately 75 percent of Best Buy's 4,500 corporate office employees participate in ROWE. Large employers in the priced corridor (the overall region is home to 20 Fortune 500 companies and 33 Fortune 1000 companies) were targeted for participation, with the goal of reducing 500 daily peak-period trips through the corridor.

Smart Navigation Systems

Very Large Urban Areas

Smart Mobility Network (SMN) - San Francisco, California

The Smart Mobility Network in San Francisco is a project aimed at improving traffic flow and reducing congestion. It utilizes a combination of real-time traffic data, connected vehicle technology, and advanced algorithms to provide drivers with real-time navigation guidance, including alternate routes and dynamic signal timing adjustments. The goal of SMN is to provide real-time traffic information and dynamic routing guidance to drivers, enabling them to make informed decisions and choose the most efficient routes (Lee, Hancock, Hu, & Change, 2014). Real-Time Traffic Data, Connected Vehicle Technology, Dynamic Routing Guidance, Signal Timing Adjustments, and Integration with Transit Services are the key components to enable smart navigation in San Francisco. Utilizing these elements, the program seeks to assist drivers in steering clear of congested areas and contribute to alleviating traffic congestion.

Large Urban Areas

Smart Work Zone Navigation – Minneapolis-St. Paul, MN

The SWZ Navigation project in Minnesota aims to improve safety and minimize delays in work zones. It uses technologies such as GPS, mobile applications, and dynamic message signs to provide drivers with real-time information on work zone locations, lane closures, and alternate routes. The system helps drivers navigate through work zones more efficiently and reduces the risk of accidents. Work zones can often cause traffic congestion, crashes, and frustration for drivers, and this project aimed to mitigate those issues through the use of advanced technologies and communication systems. Here are some key parts about the SWZ Navigation project in Minnesota (Craig, Achtemeier, Morris, Tian, & Patzer, 2017; Liao, 2014):

1. Real-Time Work Zone Information
2. Dynamic Message Signs
3. Mobile Applications and Websites
4. In-Vehicle Navigation Systems
5. Traveler Advisory Radio

Using these components, the driver is alerted about the work zone locations and given an optimal path to reduce congestion caused by work zones.

Smart Navigation System in Tampa, FL

The City of Tampa has successfully implemented a system that allows navigation apps to receive real-time information about road closures, construction zones, and other events that may impact traffic flow. This information is then used by navigation apps to provide alternate routes to drivers, helping to reduce congestion.

FDOT is working on a similar project that will allow navigation apps to receive real-time traffic data from the state's traffic management system. This data will be used to provide drivers with more accurate and up-to-date information about traffic conditions, which can help them to make better routing decisions and avoid congestion.

Public Transportation Systems

Very Large Urban Areas

Los Angeles Metro

The Los Angeles Metro prioritizes enhancing mobility by expanding the rail network, improving bus services, and promoting multimodal connectivity. To reduce single-occupancy vehicle trips, the Metro invests in convenient and attractive transit options. Efforts to improve travel times involve dedicated bus lanes, signal priority, and expanding rail lines. The Purple Line Extension, Regional Connector, and Crenshaw/LAX Line contribute to a more efficient transportation system. Bus Rapid Transit lines like the Metro Orange Line and Silver Line enhance bus efficiency, while Transit-Oriented Development and last-mile connectivity initiatives encourage living, working, and playing near transit options, reducing the need for lengthy commutes.

San Francisco, CA: Geary Rapid Project

The Geary Rapid project was completed in 2021 and produced 18 percent faster travel times and an 81 percent reduction in excessive speeding (over 40 miles per hour) on the eastern stretch of Geary. Bus reliability, as measured by travel-time adherence, increased 37 percent, helping riders get to their destinations on time.

Minneapolis, MN: Hiawatha Light Rail Transit Line

In 2004, the Hiawatha LRT project was inaugurated, spanning 12 miles and connecting three prominent destinations in the Twin Cities – downtown Minneapolis, Minneapolis/Saint Paul (MSP) International Airport, and the Mall of America in Bloomington. The Hiawatha LRT project faced political opposition from the outset due to its initial cost and doubts about the ability of LRT to attract riders in an urban area predominantly oriented towards automobiles. Since its opening on June 26, 2004, and until December 2005, the Hiawatha LRT has served customers 10.9 million times, surpassing ridership projections by 65 percent. Over 50 percent of train riders are new to transit services since the commencement of rail service in 2004.

A comprehensive analysis of rail and bus ridership in the Hiawatha corridor was conducted in 2004, followed by a subsequent study in 2006. The overall growth in the number of light-rail riders has outpaced the addition of in-service hours, indicating increased productivity in terms of passengers per in-service hour. Ridership during weekends and off-peak hours has grown at a faster rate than weekdays. The Hiawatha Corridor transit system has evolved into a more valuable resource for individuals making trips for various non-work purposes since the introduction of the Hiawatha Line. The Hiawatha Corridor represents another instance of rail transit influencing lifestyle choices. Travelers in the corridor have shifted towards a more transit-oriented lifestyle, showing a preference for the train despite 80 percent of them owning cars (Transit, 2010).

Seattle Link Light Rail project

Led by Sound Transit, the Seattle Link Light Rail project aims to diminish congestion through a comprehensive approach. Objectives include expanding the light rail network to connect neighborhoods and activity hubs, improving regional connectivity, and increasing transit ridership. The project has extended the light rail system with the University Link, Northgate Link, and East Link Extensions, enhancing coverage and accessibility. Transit-Oriented Development around stations encourages compact living, while multimodal integration facilitates seamless transfers between transportation modes. Park-and-ride facilities near stations provide convenient options, and fare integration simplifies payment processes, collectively encouraging public transit use and reducing congestion in the Seattle metropolitan area.

Large Urban Areas

Denver FasTracks project

The Denver FasTracks project, led by the Regional Transportation District (RTD), aims to alleviate congestion through a multi-faceted approach. Objectives include expanding the transit network with light rail, commuter rail, and BRT corridors to reduce private vehicle reliance. Improving regional connectivity minimizes long-distance commuting, diminishing congestion on major roads. FasTracks strives to boost transit ridership by enhancing services' convenience and reliability. Actions taken involve expanding the light rail system, developing commuter rail lines like the University of Colorado A Line and B Line, implementing BRT corridors such as the Flatiron Flyer, promoting transit-oriented development, and integrating various transportation modes seamlessly for a comprehensive solution.

Cleveland, OH: HealthLine BRT

The HealthLine BRT system connects the downtown central business district with University Circle via dedicated median bus lanes along Euclid Avenue. The HealthLine operates 24 hours a day, 7 days a week. During weekday peak hours, buses arrive every five minutes. Headways increase to 15 minutes in early evening and 30 minutes late at night. The buses in HealthLine use level boarding that enables the gap between the vehicle and the platform to be no greater than 3” horizontally and 1” vertically. Greater Cleveland Regional Transit Authority (GCRTA) installed over 400 ADA ramps to station platforms and cross streets, as well as Braille signage and tactile edges on crosswalks. Bus ridership on Euclid Avenue has increased from 9,000 daily riders before the HealthLine to 16,000 passengers daily as of 2013 (Officials, 2022).

Medium Urban Areas

Sarasota County

Sarasota County Area Transit (SCAT) in Florida launched its Mobility on Demand service in June 2021, eliminating and modifying fixed routes that are under-performing, improving schedule performance, and expanding curb-to-curb service. It serves four specialized zones and operates much like sharing services such as Uber and Lyft. An OnDemand vehicle will pick up customers within 30 minutes of the ride request and take them to their destinations within the same zone. Other customers traveling similar routes may ride along.

Vehicles are like minivans and accessible for those using mobility devices or needing a ramp to board. In 2022, the SCAT rebranded. Breeze Transit and Mobility on Demand became Breeze on Demand, gaining 5.2 percent, to 2.18 million trips in 2023.

Small Urban Areas

Oakland, CA: Tempo BRT

The Tempo BRT service runs along a 9.5-mile-long corridor from downtown Oakland to the San Leandro Bay Area Rapid Transit (BART) station. Riders now benefit from 5- to 10-minute headways throughout the day, bus-only lanes, off-board fare payment, all-door boarding, and comfortable, canopied stations. BRT is often conceived as a faster, cheaper way than light rail to upgrade a transit route. However, permitting and environmental review, complicated power-sharing agreements among different jurisdictions, and a lack of internal capacity to deliver big projects can slow down the process and add expense. Tempo opened in 2020, 20 years after planning began.

Richmond, VA: Pulse BRT

Greater Richmond Transit Company (GRTC) Pulse is a modern, high-quality, high-capacity rapid transit system that serves a 7.6-mile route along Broad Street and Main Street, from Rocketts Landing in the City of Richmond to Willow Lawn in Henrico County. It was launched in 2018 in partnership with GRTC, the U.S. Department of Transportation, the Commonwealth of Virginia (Virginia Department of Rail and PT - DRPT and Virginia Department of Transportation - VDOT), the City of Richmond, and Henrico County. Since it began operating in June 2018, Richmond's Pulse has driven its way to becoming one of the most successful bus rapid transit services in the country. The Pulse has exceeded ridership expectations since its launch (GRTC Transit System, 2024).

Manatee County Area Transit (MCAT)

Since November 2022, Manatee County Area Transit (MCAT) offers free-of-charge to all riders as part of a pilot program, eliminating the $1.50 fare. The decision to implement the free fare ride was based on the rationale that the collected revenue represents a relatively small portion of the overall transit budget. According to the most recent data, MCAT's monthly public transit ridership has increased by 57 percent compared to the previous year.

Congestion and Road Pricing

Very Large Urban Areas

Road Pricing on the Puget Sound, Seattle, WA

The Puget Sound region in Washington State, which encompasses Seattle, has one of the largest regional HOV systems for many years, featuring 235 miles of managed facilities (FHWA Office of Operations 2015). The first generation of High-occupancy Toll (HOT) lanes were implemented in 2006 as a pilot project with the conversion of a single HOV lane to a HOT lane over a nine-mile section of SR-167 between Auburn and Renton, Washington (Intelligent Transportation Systems Joint Program Office 2010). This initial conversion was considered a success and was made permanent. Studies showed that variable tolling on SR-167 made more efficient use of carpool lanes without delaying buses. One year after the HOT lane installation, traffic speeds in general purpose lanes increased by 21 percent while average traffic volume increased by 11 percent. Traffic speeds in HOT lanes also increased by 6 percent after its conversion from HOV to HOT.

Following the successful implementation on SR-167, the Washington State Department of Transportation (WSDOT) began considering an expansion of HOT lanes onto I-405 with a long-term vision of creating a seamless 50-mile network along the Puget Sound's East Side Corridor. In September of 2015, WSDOT opened two express toll lanes in each direction (one new lane and one converted HOV lane) on a 17-mile stretch of I-405 (Schmit, Khani, & Zhang, 2018). A key feature in creating this vision has been the continuous interagency planning and collaboration between WSDOT, King County Metro (transit provider), and the Puget Sound Regional Council. Altogether more than 20 agencies are involved in the Eastside Corridor express toll lane project. WSDOT was able to manage these diverse interests through an executive committee that coordinated state, regional, and local interests. In addition, the agencies led a strong public process, identifying champions in both the public and private sectors (FHWA Office of Operations 2015).

Congestion Pricing in New York City, New York

New York City has made several attempts to implement congestion pricing to address traffic congestion in Manhattan. In 2019, the state legislature approved a plan to charge drivers for entering Manhattan below 60th Street. This could potentially reduce the number of vehicles entering the city by almost 20 percent, reducing congestion in the district (Kaske, 2024). As of January 5, 2025, New York City implemented Phase 1 of its congestion pricing initiative, the Central Business District Tolling Program. This program imposes fees on vehicles entering designated areas, with rates varying by vehicle type. With E-ZPass, passenger vehicles are charged $9.00 per trip, commercial trucks and buses between $14.40 and $21.60, motorcycles $4.50 per day, and taxis $0.75 per trip. The tolls are in effect during most of the day, 5 a.m. to 9 p.m. on weekdays and 9 a.m. to 9 p.m. on weekends—with the goal of alleviating traffic congestion and promoting alternative transportation options.

Preliminary results at the end of January indicate one million fewer vehicles entered the congestion zone since the program's launch, with Hudson River inbound trips improving by 10% to 30% compared to the previous year. Additionally, pedestrian activity surged, with 35.8 million people entering the congestion zone in the first four weeks, 1.5 million more than during the same period in 2024. Foot traffic within the Business Improvement District also saw a 7% increase, signaling a shift toward more walkable and transit-friendly urban mobility (Allen, 2025).

Congestion Pricing in San Francisco, California

San Francisco has explored congestion pricing as a potential solution to address traffic congestion in the city. Various proposals have been discussed, including charging drivers for entering certain areas during peak hours or implementing tolls on specific bridges. The Golden Gate Bridge Transportation District charges vehicles entering the Bay area on the southbound entry on the bridge. An analysis conducted in 2010 regarding congestion pricing in San Francisco, the following advantages were identified: a decrease of 12 percent in peak period automobile trips, a reduction of 21 percent in vehicle delay, and an enhancement of transit speeds by 20 percent to 25 percent (SFMTA, 2020).

Other Examples

Congestion Pricing in Other Parts of the World

Various cities worldwide have implemented congestion pricing. Some of the cities are Stockholm, London, Milan, and Gothenburg. Delays were reduced in all these cities. Specifically, there was a reduction of 33 percent for Stockholm, 30 percent for London and Milan, and 10 percent to 20 percent in Gothenburg (WSTC.gov, 2019).

Connected and Automated Vehicles (CAVs)

Very Large Urban Areas

New York City, NY

In New York, there was a CAV pilot that was part of the larger ITS Joint Program Office project that involved three cities – New York, Tampa, and Wyoming. The pilot tested vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication systems. Improvements in safety and traffic management were tested through real-time data exchange between vehicles and the infrastructure. Safety signals, signal phase, and timing messages are a few of the things tested in this pilot (Dyson, 2021).

The New York City Connected Vehicle Pilot (NYC CV Pilot) has produced significant findings in various areas. The pilot successfully equipped approximately 3,000 vehicles and installed 450 roadside units (RSUs) throughout Manhattan and Brooklyn. These installations enabled the deployment of 13 safety applications designed to provide real-time alerts to drivers. These alerts helped prevent collisions, manage vehicle speeds, and improve pedestrian safety by warning drivers of potential forward collisions, lane change crashes, work zone approaches, speeding, and red-light violations. This initiative significantly enhanced overall road safety in the pilot areas (C2SMARTER, 2021; ITS-JPO, 2022).

One of the standout applications focused on pedestrian safety involved a mobile-accessible pedestrian signal system aimed at assisting visually impaired pedestrians. This system utilized personal information devices to communicate signal timing and intersection geometry through audio and haptic feedback. This technology greatly assisted visually impaired individuals in safely navigating intersections, providing an essential tool for enhancing pedestrian safety in a bustling urban environment (C2SMARTER, 2021; ITS-JPO, 2022). The NYC CV Pilot included comprehensive data collection and performance evaluation, employing both simulated and observed data to measure the safety impacts of the deployed technologies.

A key metric used in these evaluations was "time-to-collision," which helped in assessing the effectiveness of the connected vehicle technology in reducing the risk of crashes. This rigorous evaluation process provided valuable insights into the safety benefits of the pilot (C2SMARTER, 2021). The deployment faced and addressed several technical challenges unique to New York City's dense urban environment. These included issues like signal interference and positioning accuracy within the city's "urban canyons." The system design had to balance the need for providing timely alerts to drivers without causing excessive distractions. This was achieved by implementing audio-only human-machine interfaces (HMIs), which delivered alerts through tones and verbal instructions, thereby minimizing driver distraction while maintaining safety (ITS-JPO, 2022).

The CV Pilot strongly supports New York City's Vision Zero goals, which aim to eliminate traffic fatalities and severe injuries. By integrating connected vehicle technology, the pilot demonstrated significant potential in reducing crash frequencies and managing vehicle speeds. These advancements contribute to creating safer streets and align with the city's broader objectives of enhancing road safety for all users (ITS-JPO, 2022).

Large Urban Areas

St. Petersburg-Tampa, FL (Tampa-Hillsborough Expressway Authority Connected Vehicle Pilot)

The Tampa-Hillsborough Expressway Authority (THEA) Connected Vehicle Pilot in Tampa, Florida, deploys DSRC technology along a 10.6-mile stretch of the Lee Roy Selmon Expressway. The project aims to enhance safety and reduce congestion by enabling real-time communication between vehicles and infrastructure. Applications include signal phase and timing (SPaT) broadcast, queue warnings, and work zone warnings. Rigorous evaluation, including data collection and user feedback, will inform future deployment plans. The pilot demonstrates how connected vehicle technologies improve traffic flow, optimize signal operations, and empower drivers with real-time information to reduce congestion on major roadways.

Columbus, OH (Smart Columbus Program)

The smart Columbus initiative leveraged cutting-edge technologies to create an efficient and sustainable transportation system through the integration of CAVs. Electric Autonomous Vehicles (EAVs) were introduced in a pilot study to address last-mile transportation needs, aiming to reduce congestion and enhance mobility. The study focused on creating a connected vehicle environment, fostering communication between CAVs and infrastructure like traffic signals. As part of the program, Columbus collaborated with automated vehicle technology companies to integrate advanced sensors and AI into CAVs, which help reduce congestion. Extensive data collection and analysis were done to evaluate CAV performance, safety, and impact on traffic patterns.

Phoenix, AZ (Waymo)

In 2018, Waymo launched the world’s first commercial autonomous ride-hailing service in Phoenix, Arizona (see Figure 36). This launch allows customers to book a self-driving car through an application (app) (Barrett et al., 2019).

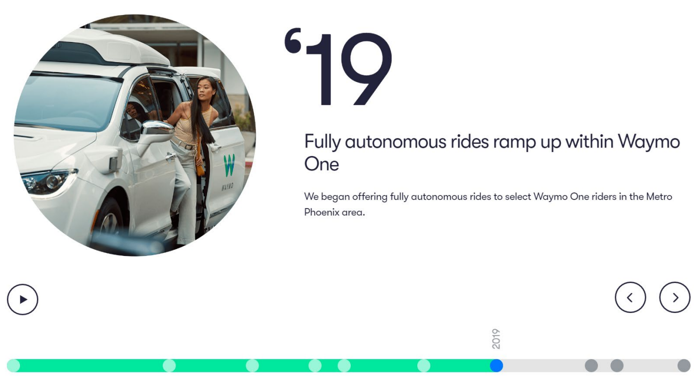


Figure 36. Waymo full autonomous rides in Phoenix.

Source: (Waymo, 2023)

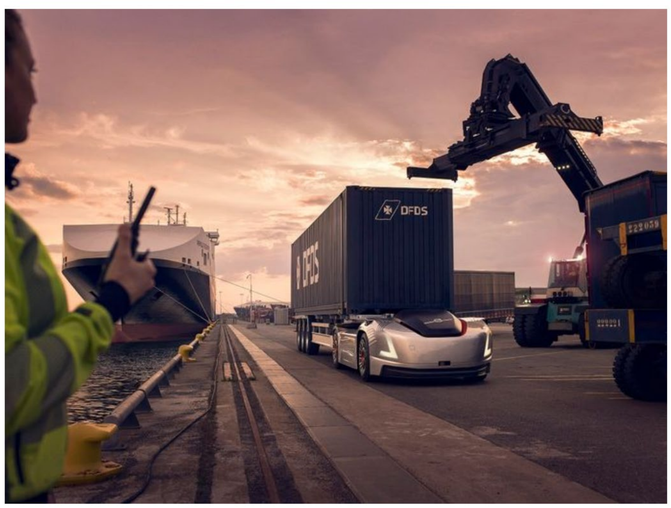
Orlando, FL

The Interstate 4 (I-4) FRAME project in Florida, known as Florida Regional Advanced Mobility Elements, is a comprehensive initiative for managing transportation across multiple counties. It spans from Tampa's Central Business District to the southwest edge of Orlando near the Florida Turnpike. Covering a total of 77 miles along I-4 and 122 miles on other limited-access routes, as well as signalized arterial roads, the project aims to integrate transportation systems over a significant distance, involving Hillsborough, Polk, Osceola, and Orange counties, incorporating a total of 491 traffic signal systems. There are various safety and mobility applications like reduced speed zone warning, work zone management, incident scene safety monitoring, transit and freight signal priority, etc. that are planned to be implemented on the I-4 to improve mobility and safety.

Medium Urban Areas

Gothenburg, Sweden (Vera, Volvo autonomous truck moving goods)

Volvo from Sweden partnered with Uber in 2016 to generate a fully autonomous vehicle system. The vehicle had multiple backup features for steering, braking, and battery power, which enabled it to stop in case of emergency. Additionally, Volvo Trucks partnered with the ferry and logistics company DFDS to create a connected electric autonomous vehicle named "Vera" (Figure 37). The goal of the CAV was to help in the transportation of goods between a logistic center to a port terminal in Gothenburg, Sweden. "The joint venture aimed to design a repetitive and continuous flow operating under 40 kph (25 mph) that is responsive to demands, while maintaining maximum efficiency, flexibility, and sustainability" (Neufville et al., 2022).



Volvo's new Vera autonomous, all-electric tractor, is moving goods in the port city of Gothenburg, Sweden.

Photo: Volvo Trucks

Figure 37. Vera, Volvo autonomous truck moving goods.

Source: (Staff, 2019)

Small Urban Areas

Ann Arbor, MI

Ann Arbor, Michigan is using smart signals. The Ann Arbor Smart Signal project, led by UMTRI, enhances safety with more than 20 smart intersections equipped with sensors to provide real-time data to connected vehicles.

Funded by a $9.95 million grant and $10 million from partners, it aims to demonstrate and scale CAV technologies, reduce traffic congestion, and create a blueprint for national deployment (Achtenberg, 2022; Lynch, 2021; Sokotoff, 2021).

Salt Lake City, UT

Salt Lake City, Utah is one of the cities that are using CAV for transit signal priority. The Salt Lake City Connected and Automated Vehicle (CAV) TSP project has enhanced bus transit efficiency. Utilizing DSRC technology, buses communicate with traffic signals to extend green lights, improving on-time performance from 88 percent to 94 percent on Redwood Road and reducing schedule deviations on the UVX route by 7.6 percent. The system minimally impacts general traffic and plans are underway to expand this technology to other major corridors (Schultz, 2022; UDOT, 2023).

Other Examples

Although CAVs will not be prevalent in decades, there are a few deployments across the county and the world. By looking at the individual features, many good examples of implementation already exist. For example, antilock brakes for automated warnings in case vehicles depart from lanes is a CAV feature that is helping with safety. There are currently 170 plus deployments that are planned or in progress. Most of them are of the connected vehicle technology type. While there have been successful connected vehicle projects, it is important to note that the specific percentage reduction in congestion and improvement in safety can vary based on the project, location, and other factors. Certain coverage of the connected vehicle is achieved at the national level.

In the United Kingdom, an autonomous Nissan LEAF equipped with systems enabling single-lane autonomous driving was pilot tested in February 2017. The autonomous vehicle could navigate roads and obstacles, change lanes, merge with traffic, and come to a stop or move off at the appropriate time while traversing a roundabout or signal-controlled junction (Neufville et al., 2022). FHWA demonstrates some platooning (only for demonstration).

Wyoming used CAVs and improved the travel time of goods movement. The state's connected vehicle technology focused on adverse weather conditions affecting non-recurring congestion. They showed that the technologies were very useful in terms of improving travel times for the movement of goods on Interstate travels since they deployed the technology using commercial and fleet vehicles.

Advanced Transportation Technology

Large Urban Areas

Package Delivery Robots in Charlotte, NC; Bowling Green, OH

There is a growing trend of utilizing the advancements in robotics and automation to simplify last-mile deliveries. These emerging technologies play a vital role in reducing congestion and improving mobility by reducing the number of vehicles on the roadway. Package delivery robots are autonomous and self-driven robots that are being employed to transport packages like food, medicine, groceries, etc., from the vendor to the customer for shorter distances. One such project can be seen in the University of North Carolina at Charlotte where dining services have teamed up with Starship Technologies to deliver food for faculty and students within the campus. This is a pilot project where robots are delivering food from dining halls. These robots use sidewalks and pedestrian pathways to alleviate traffic congestion. These robots can also work around the clock to make deliveries using optimized routes and schedules. This will reduce traffic congestion, delivery time, emissions, and cost. This pilot is also implemented in Bowling green, OH.

Small Urban Areas

Amazon Air Drone Delivery

Amazon Air's drone delivery service represents a cutting-edge approach to logistics, utilizing unmanned aerial vehicles (UAVs) to transport packages efficiently (Jung & Kim, 2017). This innovative delivery method promises faster delivery times and reduced carbon emissions compared to traditional delivery methods (Sudbury & Hutchinson, 2016). Through advanced technology and rigorous safety protocols, Amazon aims to revolutionize the delivery industry by providing swift and reliable service directly to customers' doorsteps using autonomous drones. Currently, these drones will be delivering packages in two locations in the United States – College Station, Texas and Lockeford, California and to three additional U.S. locations as well as some cities in Italy and the UK by the end of 2024 (Amazon, 2023; Chen, 2023). By bypassing ground-based transportation routes, drones can deliver packages directly from the warehouse to the customer's location. This eliminates the need for delivery trucks or vans to navigate through congested roads, thereby reducing traffic congestion. Drones excel at covering the "last mile" of delivery, which is often the most congested and challenging part of the delivery process. By efficiently navigating this segment, drones can alleviate congestion typically caused by delivery vehicles navigating narrow streets or crowded neighborhoods (Singireddy & Daim, 2018).

Emerging Technologies

Very Large Urban Areas

Hyperloop

The Hyperloop is a proposed high-speed transportation system that uses low-pressure tubes to transport passengers and cargo at extremely high speeds. Companies like Virgin Hyperloop and SpaceX are working on developing and commercializing this technology. The Hyperloop could significantly reduce travel times between cities and has the potential to revolutionize long-distance transportation (Dudnikov, 2017). The Hyperloop envisions a network of low-pressure tubes through which passenger pods or capsules travel at extremely high speeds, using magnetic levitation and vacuum technology to reduce air resistance and friction (Abdelrahman, Sayeed, & Youssef, 2017; Nøland, 2021). The Hyperloop has the potential to revolutionize long-distance transportation by significantly reducing travel times between cities. It could offer a more sustainable and efficient alternative to air travel, reduce congestion on highways, and provide increased mobility options for both passengers and cargo. Hyperloop routes would typically connect major cities and urban centers. Stations would be strategically located to facilitate passenger boarding and disembarking. The system could potentially integrate with existing transportation infrastructure, such as airports and train stations, to provide seamless connections. There are many routes planned by various Hyperloop companies, including:

1. Toronto–Montreal
2. Cheyenne–Denver–Pueblo
3. Miami–Orlando
4. Dallas–Laredo–Houston
5. Chicago–Columbus–Pittsburgh

6. Mexico City–Guadalajara
7. Edinburgh–London
8. Glasgow–Liverpool
9. Bengaluru–Chennai
10. Mumbai–Chennai
11. Los Angeles – San Francisco

Not all of these routes are operational at this moment with a few being used for pilot studies or case studies. For example, the Los Angeles to San Francisco Hyperloop is planned to reduce travel times to 35 minutes for the 380-mile trip (Walravens, 2020). The Mumbai-Pune hyperloop will cut travel times to 25 minutes from 180 minutes (Premsagar & Kenworthy, 2023).

Uber Elevate in Los Angeles, CA; Dallas, TX; and Melbourne, Australia

Uber Elevate is a project initiated by Uber Technologies Inc. aimed at developing urban air mobility (UAM) solutions, including flying taxis and drone delivery services. The goal of Uber Elevate is to revolutionize transportation by introducing aerial ridesharing services that can bypass traffic congestion and provide faster transportation options within cities (Uber, 2024). The project envisions electric-powered aircraft that can take off and land vertically, providing efficient and environmentally friendly transportation alternatives. These aircraft would operate from "vertiports," which are like helipads but designed specifically for UAM vehicles. Uber Elevate has been collaborating with aircraft manufacturers, regulatory authorities, and infrastructure developers to bring its vision of urban air transportation to reality. While the concept of flying taxis and drone delivery services is still in the developmental stage, Uber Elevate represents a significant effort towards transforming the future of urban mobility. They aim to launch this service in Los Angeles, Dallas, and Melbourne, Australia (Society, 2023).

Lessons Learned

The literature review and interviews provided lessons learned from the implementations of the various congestion reduction areas covered in the project. This section lays out those lessons learned by congestion reduction areas next. No lessons learned were obtained related to advanced and emerging transportation technologies.

Smart and Advanced Signal Timing and Optimization Systems

The summary of lessons learned from traffic signal timing experts is provided below:

- **Incorporate All Modes:** The smart and advanced signal timing process must account for all modes of transportation, including buses, cyclists, pedestrians, and cars, to ensure equitable and efficient traffic management.
- **Establish Clear Objectives:** Define clear goals for addressing traffic issues and create a roadmap for translating these objectives into practical solutions and tangible benefits.
- **Align Objectives with Policies:** Engineers and agencies should ensure their objectives are consistent with and support the overarching policies of the city or region.
- **Engineer-Vendor Collaboration:** Engineers must leverage their expertise alongside vendor-provided equipment. Vendors, in turn, must offer reliable, well-designed products that are easily maintained by

agencies. Success depends on engineers having the right concepts and vendors providing the right tools.

- **Beware of Overstated Claims:** Some vendors overpromise the capabilities of adaptive signal control systems, claiming they can solve all issues. In practice, these systems have limitations and should be implemented with realistic expectations.
- **Long-Term Role of Engineers:** Fifteen years ago, it was predicted that adaptive signal control would eliminate the need for traffic signal engineers, but this has proven untrue. Adaptive signals are effective for certain corridors but require periodic updates, much like conventional signal timings, as they age, and traffic patterns evolve.
- **Communication and Detection:** Ensuring effective communication and detection systems can address some congestion issues related to signal timings. However, as connected vehicle technology advances, the reliance on traditional detection systems will diminish.
- **Address Systemic Issues:** Smart and advanced signal timing and optimization systems are valuable tools but are not standalone solutions for congestion. Comprehensive, systemic changes are necessary to achieve significant reductions.
- **Promote Proven Technologies:** Demonstrating documented success and reliability increases the likelihood of adoption and trust in smart and advanced signal technologies.

The lessons learned from the implementations of smart and advanced signal timing and optimization from a different study include the following (Stevanovic, 2010):

- Better local support from the vendors,
- Better planning for in-house operational and institutional support,
- A good preparation of the infrastructure (detection and communications), and
- Detailed pre-installation evaluation to estimate the operational benefits of the ATCS.

Traffic Incident Management

The summary of lessons learned from TIM experts is provided below:

- **Tailored Incident Management Plans:** The effectiveness of incident management strategies is highly location-dependent. What works well in one area may not be effective in another, even in seemingly similar environments. Each location has unique circumstances and characteristics that must be considered. Implementing a one-size-fits-all approach can lead to unintended consequences. To achieve successful outcomes, it is crucial to customize strategies to address the specific needs and conditions of each area.
- **Emphasize Flexibility and Collaboration:** Flexibility is essential in developing incident management plans. These plans should be adaptable to changing circumstances and incorporate continuous, constructive communication among all responding agencies. Effective collaboration ensures coordinated efforts, enhances decision-making, and improves response efficiency.

Transportation System Management and Operations (TSM&O)

The summary of lessons learned from the experts in TSM&O is provided below:

- **Leverage TSM&O Solutions via Agency Collaboration and Coordination:** Collaboration agreements between jurisdictions and agencies are vital for effective TSM&O strategy implementations.

Coordinated efforts among multiple entities are essential to ensure seamless operations and successful outcomes.

- **Raise Awareness of TSM&O:** Public education about TSM&O is crucial. Increasing awareness of how TSM&O strategies enhance safety and roadway reliability fosters public support and understanding of these initiatives.
- **Prioritize Traveler Information:** Providing accurate and timely traveler information is critical. If an agency lacks the capacity to do so, forming partnerships with other capable agencies can ensure this vital service is delivered effectively.

Multimodal Transportation Systems

The summary of lessons learned from the experts in the multimodal transportation systems is provided below:

- **Public Education and Cultural Shift beyond Infrastructure:** Developing a successful multimodal transportation system requires more than constructing infrastructure. Educating the public about how to use the system and highlighting its benefits is essential. Equally important is fostering a cultural shift to encourage acceptance and adoption of diverse transportation modes and behaviors. Education plays a pivotal role in driving this transformation.
- **Clarify the Purpose of Multimodality:** The goal of multimodality is not simply to reduce the number of vehicles on the road but to provide equitable access to a variety of transportation options—such as transit, walking, and cycling. It is about creating inclusive roadways that accommodate and serve all users effectively.
- **Integrate Multimodal Approaches:** Incorporating multimodal strategies into transportation planning demonstrates the development of a well-rounded and adaptable transportation network. This approach ensures the system meets the specific needs of the area while benefiting all users, enhancing mobility and accessibility for everyone.

Shared Transportation Systems

The summary of lessons learned from the experts in the shared transportation systems is provided below:

- **Enhance Connectivity Through Integration:** Combining shared transportation services with existing infrastructure—such as public transit networks, bike lanes, and pedestrian pathways—can significantly improve connectivity and accessibility, creating a seamless travel experience for users.
- **Harness Technology and Data Analytics:** Utilizing technology and data-driven solutions can optimize shared transportation systems. Real-time information, mobile applications, and intelligent routing algorithms improve operational efficiency, enhance service delivery, and provide a superior user experience.
- **Focus on User-Centered Design:** The success of shared transportation systems relies on delivering an excellent user experience. Key factors include ease of use, reliability, affordability, and convenience, all of which play a critical role in encouraging adoption and sustained use.

Telecommuting and Flexible Work Hours

The summary of lessons learned from the traffic demand management experts is provided below:

- **Engage Employers in Congestion Solutions:** Some employers may not prioritize road congestion when planning work schedules. It is essential to maintain ongoing discussions about congestion and highlight positive examples, emphasizing how reducing or eliminating travel time benefits employees. This not only enhances their well-being but also contributes to greater overall productivity and satisfaction.

Smart Navigation Systems

The summary of lessons learned from the experts in smart navigation systems is provided below:

- **Behavioral Preferences in Transportation:** Many individuals tend to choose their mode of transportation in advance rather than relying on navigation apps to make real-time decisions.
- **Collaboration for Success:** Successful implementation of smart navigation systems requires strong collaboration between local governments and transportation agencies to ensure alignment and effective deployment.
- **Public Education on SNS Benefits:** Educating the public on the benefits and effective usage of smart navigation systems is crucial to maximizing their impact on traffic management and overall efficiency.
- **Integration for Optimal Performance:** To fully realize the potential of smart navigation systems in improving traffic flow and reducing congestion, seamless integration with other transportation systems is essential.

Public Transportation Systems

The summary of lessons learned from the PT professionals is provided below:

- **Collaboration is Key for BRT Success:** The success of BRT systems heavily relies on effective collaboration among agencies. Without alignment and agreement, these projects cannot move forward.
- **Social Norms Affect Public Transportation Usage:** The adoption of PT is influenced by prevailing social norms, with many individuals hesitant to embrace it due to established habits and perceptions.
- **Overcoming Car Travel Preference:** There is a strong cultural preference for car travel, making it challenging to shift public attitudes toward alternative modes of transportation.
- **Increasing Public Transportation Ridership to Reduce Congestion:** PT can effectively reduce congestion with higher ridership. To achieve this, commuting times for public transport should be competitive with car travel times. For buses, this can only be realized with dedicated lanes to avoid delays caused by traffic congestion, ensuring they operate faster and more efficiently than private vehicles.

Congestion and Road Pricing

The summary of lessons learned from the professionals in congestion and road pricing is provided below:

- **Critical Design Considerations for Pricing Schemes:** The effectiveness of congestion and road pricing schemes depends on thoughtful design. Key factors include pricing levels, exemptions, and implementation strategies, all of which must be carefully tailored to achieve desired outcomes.
- **Emphasize Flexibility and Adaptability:** Flexibility in implementation is essential for success. Pricing schemes should be adaptable, allowing for adjustments based on real-world outcomes and feedback from stakeholders to ensure long-term effectiveness.

- **Prioritize Monitoring and Evaluation:** Continuous assessment is crucial to evaluate the impacts of congestion pricing. This includes tracking traffic flow, air quality, equity outcomes, and economic effects, as well as making necessary adjustments to optimize results.
- **Complementary Measures Enhance Effectiveness:** Congestion and road pricing are most successful when paired with complementary strategies. These include investments in PT, active transportation infrastructure, and land use policies that promote denser, transit-oriented development patterns.

Connected and Automated Vehicles (CAVs)

The summary of lessons learned from the CAV experts is provided below:

- **Connectivity is Essential for Progress:** The absence of connectivity has hindered significant progress. Without connectivity, efforts to reduce congestion will remain ineffective.
- **Collaboration across Industries:** Close collaboration with other industries is critical to advancing innovative solutions and achieving success in congestion reduction efforts.
- **Controlled Testing for Vendors:** Testing vendor technologies in controlled environments is essential to evaluate their effectiveness and suitability before full-scale deployment.
- **Shift Away from On-Board Units (OBUs):** Relying on OBUs is not ideal, as drivers may discard them due to privacy concerns, as seen in THEA's experience with 1,300 OBUs. Instead, investing in Vehicle-to-Everything (V2X) data exchange platforms offers a more viable and scalable solution.
- **Protecting Privacy in Data Collection:** Personal Identifiable Information (PII) should not be collected during data collection processes. Instead, data should be aggregated to ensure user privacy while still enabling meaningful insights.

Resource Guide

This resource guide highlights materials and work related to congestion. There are several congestion research activities and congestion documents. Some of those documents are listed below.

General Congestion

- Urban Mobility Study, http://mobility.tamu.edu/ums, sponsored by 10 state DOTs
- Mobility Monitoring Program, http://mobility.tamu.edu/mmp, sponsored by the Federal Highway Administration with 23 participating cities
- Quantifying Congestion, sponsored by the National Cooperative Highway Research Program, published as NCHRP Report 398
- Travel Time Data Collection Handbook, available at http://tti.tamu.edu/, sponsored by Federal Highway Administration
- How to Fix Congestion Texas A&M Transportation Institute

Smart and Advanced Signal Timing and Optimization Systems

- Adaptive Traffic Control Systems: Domestic and Foreign State of Practice. A Synthesis of Highway Practice, http://elibrary.pcu.edu.ph:9000/digi/NA02/2010/14364.pdf
- Adaptive Signal Control Technology, https://www.fhwa.dot.gov/innovation/everydaycounts/edc-1/asct.cfm, by the United States Department of Transportation Federal Highway Administration.

Incident Management

- Traffic Incident Management Gap Analysis Primer, https://ops.fhwa.dot.gov/publications/fhwahop15007/chapter1.htm
- Introduction to Traffic Incident Management, https://ops.fhwa.dot.gov/tim/publications/timhandbook/chap1.htm
- Design Guide for Addressing Nonrecurrent Congestion, https://nap.nationalacademies.org/read/22475/chapter/5

TSM&O

- The FHWA TOPS-BC tool for sketch-planning of operations benefits, https://ops.fhwa.dot.gov/plan4ops/topsbctool/index.htm
- TSMO Benefits at a Glance (examples of TSMO benefits from various locations), https://ops.fhwa.dot.gov/publications/fhwahop21054/index.htm
- TSMO in Rural Areas, https://ops.fhwa.dot.gov/resources/news/news_detail.asp?ID=1178
- Coordination of Information Technology and TSMO, https://ops.fhwa.dot.gov/resources/news/news_detail.asp?ID=1174
- NCHRP 03-126 (Developing an Operations Manual for AASHTO), https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4178
- TxDOT's I-35 Project Website, https://my35.org/index.htm
- What is TSM&O? https://ops.fhwa.dot.gov/tsmo/
- Fact-sheet, https://ftp.txdot.gov/pub/txdot-info/trf/tsmo/fact-sheet.pdf
- TSM&O fact sheet (Upcoming)

Multimodal Transportation

- Multimodal Transportation Planning: Multimodal Transportation Planning – Simple Book Publishing (pressbooks.pub)
- Multimodal Access to Public Transportation, Multimodal Access to Public Transportation | US Department of Transportation
- Introduction to multi-Modal Transportation Planning: Principles and Practices, https://www.vtpi.org/multimodal_planning.pdf

Shared Transportation Systems

- The Benefits of Carpooling, https://escholarship.org/uc/item/7jx6z631
- Shared Mobility in 2022, Shared Micromobility in 2022 | National Association of City Transportation Officials (nacto.org)
- Commute Mode Share, https://www.transportation.gov/mission/health/commute-mode-share

Telecommuting and Flexible Work Hours

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Chapter 5. Conclusions

Traffic congestion occurs when the volume of vehicles on the road exceeds the roadway capacity or reduced capacity due to crashes, incidents, and work zone activities, leading to reduced speeds and unstable traffic flow. Beyond its impact on mobility, congestion adversely affects public health and quality of life. Prolonged delays in traffic can contribute to mental health challenges due to increased stress and frustration. Congestion is generally classified into two categories: recurring and non-recurring, each stemming from different causes and requiring tailored solutions.

The rapid emergence and evolution of strategies and technologies have expanded the range of options available to address congestion challenges. However, despite the wealth of existing documentation on congestion, the project team identified a gap in having a comprehensive roadmap and resource guide to holistically address congestion mitigation strategies.

The primary objective of this research was to develop a detailed roadmap and supporting resources for congestion reduction. This roadmap encompasses major and emerging congestion mitigation strategies, their subareas, timelines for implementation, expected impacts, interrelationships, successful case studies, lessons learned, and the steps for utilizing the roadmap including: (1) Identify Key Challenges, (2) Leverage Best Practices, and (3) Plan for Future Growth. A comprehensive resource guide was created as part of the project.

To construct this roadmap, the team conducted an extensive literature review and in-depth interviews with experts. These efforts provided insights into various strategies, approaches, current and future technologies, as well as their benefits, limitations, uncertainties, and interconnections. The result is a robust, actionable guide designed to help practitioners, policymakers, and researchers tackle congestion effectively and sustainably.

The 12 major congestion mitigation areas outlined in this report offer diverse solutions to reduce or manage traffic congestion, with each playing a distinct role or contributing collectively when combined. While some strategies are more effective for addressing recurring congestion, others excel in mitigating non-recurring issues. Certain approaches are particularly suited to very large and large urban areas, while others are more applicable to medium and small urban areas, and vice versa. Several strategies or approaches prove universally effective regardless of recurring or non-recurring congestion or metropolitan area size. Technological solutions, in particular, are anticipated to deliver greater benefits in the future as advancements continue. Each area presents unique benefits, limitations, and uncertainties, and while some connections between these areas are stronger than others, all are interrelated to varying degrees. Additionally, successful case studies and lessons learned are documented for most areas, offering practical insights and guidance for effective implementation.

Reducing traffic congestion should not always be the primary focus in every context, as congestion can sometimes encourage the adoption of alternative transportation modes. In some cases, traffic congestion makes options such as public transit—including buses, trains, and ferries—as well as walking and cycling, more competitive and appealing. A more sustainable and impactful approach, especially in large and very large urban areas, involves prioritizing public transportation, multimodal and shared transportation strategies that improve transit efficiency and reduce delays for drivers, pedestrians and cyclists. Investments in multimodal infrastructure not only address congestion but also provide broader benefits, such as economic development and enhanced urban mobility.

Achieving substantial congestion reduction is challenging as long as private cars remain the dominant mode of transportation, underscoring the importance of offering diverse and accessible transportation options. For small and medium urban areas, smart and advanced signal timing proves particularly effective in reducing congestion. In larger urban areas, such strategies remain essential but should be complemented by incident management, TSM&O, telecommuting, and flexible work hours, which are universally beneficial for mitigating congestion.

When addressing transportation and congestion, it is essential to broaden the conversation to include land use. In North America, congestion often focuses on vehicular traffic on roadways, framed as a spatial issue of cars, road capacity, and signal timing. However, tackling congestion solely from a vehicle-centric perspective leads to more vehicles. Instead, land use and zoning should be key considerations. Shifting the focus from maximizing highway efficiency to creating zoning policies that place services and businesses closer to neighborhoods can significantly reduce congestion. By examining and optimizing land use patterns, communities can address both recurring and non-recurring congestion more effectively, fostering sustainable transportation systems and reducing reliance on cars.

Effectively addressing congestion requires a comprehensive, context-sensitive approach that tackles both recurring and non-recurring traffic challenges. Key strategies include implementing advanced traffic signal systems to optimize traffic flow, adopting TSM&O to enhance overall efficiency, and developing robust incident management plans to minimize delays caused by unforeseen events. Promoting multimodal transportation—such as integrating public transit, cycling, and walking infrastructure—alongside shared mobility options is crucial for creating a balanced and accessible transportation network.

Land-use planning that reduces trip lengths by situating services and businesses closer to residential areas also plays a vital role in managing congestion. In large cities with strong public transit systems, introducing congestion pricing can further reduce traffic volumes. Moreover, investments in sustainable urban design and pedestrian and cycling infrastructure help reduce car dependency, easing congestion while enhancing urban livability.

While technologies such as connected and automated vehicles, smart navigation systems, urban air mobility, and advanced or emerging transportation innovations may not have an immediate impact on current congestion levels, they hold significant potential to alleviate traffic and improve safety for all road users in the future. Strategic planning and preparation for these emerging technologies will be essential for achieving long-term mobility and safety goals.

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Appendix

Interview Questions

1. What is a good definition for the congestion mitigation area?
2. What are some important subareas it includes?
3. How, why, and under what conditions can the area and its subareas help avoid or mitigate congestion?
4. Which types of congestion (recurring or/and non-recurring) can each area and related subareas address?
5. What are the current technologies used in the area and subareas?
6. How will the current technologies evolve in the future considering short-term (0-5 years), medium-term (6-15 years or 6-19 years), and long-term (16+ years or 20 +Years)?
7. How will the current and evolved technologies assist in mitigating congestion now and in the future?
8. What are the expected percentages of congestion that can be reduced by each of the solutions (the area and its subareas)? What are some of the uncertainties in the area and its subareas?
9. What are the benefits and disadvantages of the congestion mitigation area and subareas?
10. How do the area and its related subareas interact together and with other areas and subareas? How can we integrate them? Identified congestion mitigation areas include:
    - Connected and Automated Vehicles
    - Public Transportation Systems
    - TSM&O Strategies
    - Smart and Advanced Signal Timing and Optimization Systems
    - Incident Management
    - Telecommuting and Flexible Work Hours
    - Shared Transport Systems
    - Congestion and Road Pricing
    - Multimodal Transportation
    - Smart Navigation Systems
    - Advanced and Future Transportation Technologies
    - Other Emerging Technologies
11. Which roadway types, area sizes, or time of the day will need the area and subareas the most (e.g., highways, arterials, collectors, urban, sub-urban, rural, peak period, non-peak period, etc.)? Or which roadway type, area size, or time of the day will the area and subareas be most effective for?
12. What are some successful examples of implementations and lessons learned?

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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