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Traffic Flow Improvements: Quantifying the Influential Regions and Long-Term Benefits

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16. Abstract

This research is to conduct a synthesis study on the full-scale effects of Traffic Flow Improvements (TFI) strategies in terms of the influential region and the changes of gains over time. The ultimate goal is to inform MassDOT's evaluation of Congestion Mitigation and Air Quality (CMAQ) projects and their demonstrated benefits to relieve congestion and improve air quality. This synthesis consists of three main tasks: (1) a review of the commonly adopted TFI strategies and their impacts on traffic congestion mitigation and emission reduction; (2) a review of the methods for quantifying the effects of CMAQ TFI strategies; and (3) a survey of practitioners. It is found that most transportation agencies do consider the long-term impacts of TFI projects. Some agencies also take the regional impacts of a TFI project into account depending on its size and significance. However, very few agencies consider the induced demand impacts. The top two challenges for quantifying TFI benefits are: (1) lack of resources (e.g., funding, experienced staff, reliable data), well-accepted and documented tools/models, and consistent and widely-used evaluation standards; and (2) lack of project post evaluations. Based on the synthesis findings, both high-level and specific recommendations are provided.

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Traffic Flow Improvements: Quantifying the Influential Regions and Long-Term Benefits

Final Report

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Disclaimer

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Executive Summary

This study of “Traffic Flow Improvements: Quantifying the Influential Regions and Long-Term Benefits” was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

The Congestion Mitigation and Air Quality (CMAQ) Improvement Program is an important federal funding source that supports projects and programs for Massachusetts to improve air quality and reduce traffic congestion. To leverage support from CMAQ for a project, a critical step is to obtain the review approval from the CMAQ Consultation Committee to assure that the project demonstrates significant air quality benefits.

The objective of this research is to conduct a synthesis study on the full-scale effects of Traffic Flow Improvements (TFI) in terms of the influential region and the changes of gains over time. The ultimate goal is to inform MassDOT’s Office of Transportation Planning’s evaluation of CMAQ projects and their demonstrated benefits to relieve congestion and improve air quality. This TFI Synthesis project consists of three main tasks: (1) a review of commonly adopted TFI strategies and their impacts on traffic congestion mitigation and emission reduction; (2) a review of the methods for quantifying the effects of CMAQ TFI strategies; and (3) a survey of practitioners.

The review of CMAQ TFI strategies results in twelve types of strategies grouped into four main categories: (1) traffic signalization; (2) intersection infrastructure improvements; (3) highway control and management; and (4) road segment (including both highways and surface streets) infrastructure improvements. Due to the high costs associated with before-and-after studies, transportation agencies most of the time quantify the impacts of a CMAQ TFI project either qualitatively or using some analytical methods. These methods are based on different assumptions and use different performance measures, making the quantitative comparison and ranking of different TFI strategies difficult. A qualitative analysis shows that traffic signalization is the most cost-effective, followed in order by freeway/incident management, intersection improvements, and roundabouts. The potential benefits of a CMAQ TFI strategy is often site-specific. It is thus important to choose TFI strategies that best suit the unique characteristics of a specific site or area. In other words, the selection of TFI strategies should be analyzed on a case-by-case basis, although the idea to have an unambiguous ranking of all TFI strategies is appealing.

Most studies did not consider the changes of benefits over time and only analyzed the impacts for a specific year. This is not surprising, as a project’s long-term impact is complicated and can be affected by changes in (1) traffic patterns (e.g., new patterns require traffic signal timing plans to be updated); (2) deterioration of infrastructure conditions (e.g., pavement conditions), (3) travel behavior and demand (e.g., more trips provided by ridesharing like Uber, increased transit ridership), and (4) vehicle technologies (e.g., more fuel-efficient engines) and traffic composition (e.g., more hybrid and electric vehicles). Also, very few studies considered traffic redistribution across travel modes and routes as an effect of the project unless it is a major project of regional significance. In that case, travel demand models or sketch planning tools are often used.

The pros and cons of various methods for quantifying TFI strategy impacts are analyzed and compared. These methods are categorized into three groups: (1) sketch planning methods; (2) simulation methods; and (3) before-and-after studies. Sketch planning methods are mostly based on elasticity analysis, pivot-point method, and experience from previous studies to estimate TFI project mobility impacts. Many of them require users to provide assumptions in terms of elasticities and program participation rates, which may have significant impacts on the mobility analysis results. Sketch planning methods mostly rely on using emission rates generated by EMFAC, MOBILE, or MOVES and combining them with the mobility analysis results to estimate emissions reductions. Compared to four-step and activity-based travel demand models, sketch planning methods are much simpler and take less time and effort to apply. They can also take induced demand into consideration to some extent.

Simulation methods have also been widely used in evaluating TFI projects. However, coding and calibrating simulation networks can be time consuming. Sometimes they also require user assumptions as the input, particularly for modeling induced demand. This adds uncertainty and affects the accuracy of the modeling results. For evaluating small-scale projects such as intersection traffic signal retiming, induced demand typically is of less concern and in this case computer simulation is usually a good option.

Before-and-after studies are often considered a more reliable approach in evaluating TFI strategies. With before-and-after studies, the induced demand and regional impacts can be implicitly considered if the data collection times and locations are properly chosen. However, before-and-after studies are usually associated with high costs and suffer from too sparse data (due to high data collection cost).

The results of twenty-three returned survey forms suggest that the most cost-effective and popular strategies are all related to upgrading traffic signal hardware, software, and control plans. Among them, signal re-timing/synchronization is consistently considered more cost-effective and popular. One interesting finding is about Transit Signal Priority (TSP), which is unanimously considered to be one of the least popular and least cost-effective strategies, even by agencies that have adopted TSP. In general, managed lanes and grade separation are considered cost-ineffective and less popular. The result for roundabouts is quite controversial. A significant number of survey respondents considered it to be either the most cost-effective or the most popular. However, about the same number of respondents also rated it as the least cost-effective or the least popular.

The survey results also show that most responding agencies do consider the long-term impacts of TFI projects. They usually multiply a project's first year benefits by the project life expectancy. Another approach is to consider that a project benefits will decrease linearly to zero when the project's life expectancy is reached. Some agencies also take the regional impacts of TFI projects into account depending on the size and significance of the project.

This is typically analyzed using a regional travel demand model. However, very few agencies consider the induced demand impacts, likely due to the difficulty in modeling them. Based on the survey, the top two challenges for quantifying TFI benefits are: (1) lack of resources (e.g., funding, experienced staff, reliable data), well-accepted and documented tools/models (e.g., a look up table), and consistent and widely-used evaluation standards; and (2) lack of project post evaluations and "apples to apples" comparisons.

It is recommended that MassDOT should: (1) consider TFI project life expectancy, degradation of project benefits over time, future traffic demand, and future traffic characteristics when modeling long-term impacts; (2) consider the regional and induced demand impacts only for major TFI projects of regional significance using travel demand or sketch planning models; (3) expand and further improve their TFI quantification tools based on tools/models developed by the FHWA and other state DOTs, and take safety benefits and local factors into consideration; (4) invest in workforce development and research; and (5) explore nontraditional data sources and advanced data analytics for TFI project evaluation and prioritization. Additional specific recommendations are also provided for MassDOT to further improve its current CMAQ TFI project benefits quantification practices.

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List of Acronyms

Acronym	Expansion
AADT	Annual average daily traffic
ADT	Annual average daily traffic
AIMSUM	Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks
ATIS	Advanced traveler information system
ATMS	Advanced Traffic Management System
Automated-CE	Automated Methods to Find the Cost-Effectiveness of Funding Air Quality Projects
AWIS	automated work zone information system
BC analysis	Benefit-Cost Ratio analysis
CARB	California Air Resources Board
CCTV	Closed-circuit television
CDTC	Capital District Transportation Committee
CEA	Cost-Effectiveness Analysis
CFI	Continuous Flow Intersection
CM/AQ evaluation model	Congestion Mitigation/ Air Quality evaluation model
CMAQ	Congestion Mitigation and Air Quality
CMEM	Comprehensive Modal Emission Model
CO	Carbon monoxide
CORSIM	a microscopic traffic simulation software package
DMS	Dynamic Message Sign
EMFAC	EMission FACtors model
EPA	United States Environmental Protection Agency
FHWA	Federal Highway Administration
FIXiT	Future Improvement Examination Technique
GPS	Global Positioning System
HC	Hydrocarbon
HCS	Highway Capacity Software
HOT	high-occupancy toll
HOV	high-occupancy vehicle
IDAS	ITS Deployment Analysis System
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation System
LAMTA	Los Angeles Metropolitan Transportation Authority
LOS	Level of Service
ME-CMAQ	Methodologies for Evaluating Congestion Mitigation and Air Quality
MF lanes	mixed-flow lanes
MNL	Multinomial Logit Model
MOBILE	a model to estimate mobile pollutions
MOE	Measures of Effectiveness

Acronym	Expansion
MOVES	MOtor Vehicle Emission Simulator
MWCOG	Metropolitan Washington Council of Governments
NA	Not Available
NCTCOG	North Central Texas Council of Governments
NL	Nested Logit
NO_x	nitrogen oxides that are most relevant for air pollution
NRC	National Research Council
NS	statistically insignificant
NYSDOT	New York State Department of Transportation
OEM-2100™	A portable instrument, was used to measure on-road tailpipe emissions on a second-by-second basis during actual driving.
Off-Net	Off-Network
PAQONE	an Assessment Tool for Analyzing Effects of Transportation Control Measures
PARAMICS	a microscopic simulation software
PASSER	an arterial traffic signal timing software
PDF	Portable Document Format
PEMS	Portable Emission Measurement Systems
PM_{10}	PM_{10} particulate matter 10 micrometers or less in diameter
$PM_{2.5}$	$PM_{2.5}$ is particulate matter 2.5 micrometers or less in diameter
Quick-HOV	a tool for modelling the impacts of HOV lanes
RAQC	Regional Air Quality Council
RODEL	a fully interactive program for the Planning, Design, Evaluation and Analysis of Roundabouts
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SIDRA	a software package used for intersection(junction) and network capacity, level of service and performance analysis
SPR	State Planning and Research
SS-RTSP	South Snohomish Regional Transit Signal Priority
STEP model	systematic transportation evaluation and planning model
SUMO	Simulation of Urban Mobility
TCM	Transportation Control Measures
TDM	Traffic demand management
TFI	Traffic Flow Improvements
TIS	Traveler Information Systems
Transyt-7F	a traffic simulation and signal timing optimization program
TSP	Transit Signal Priority
TTI	Texas A&M Transportation Institute
VERSIT+	A approach to model road traffic emissions
VISSIM	A microscopic traffic simulation software
Vistro	a traffic engineering software
VMS	Variable message sign
VMT	Vehicle Miles Traveled

Acronym	Expansion
VOC	Volatile organic compounds

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1.0 Introduction

This study of “Traffic Flow Improvements: Quantifying the Influential Regions and Long-Term Benefits” was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

The Congestion Mitigation and Air Quality (CMAQ) Improvement Program is an important federal funding source that supports projects and programs for Massachusetts to improve air quality and reduce traffic congestion. To leverage support from CMAQ for a project, a critical step is to obtain the review approval from the CMAQ Consultation Committee to assure that the project demonstrates significant air quality benefits.

For projects in the category of Traffic Flow Improvements (TFI), transportation agencies are often challenged by two important problems: (1) how to estimate the benefits to a secondary corridor due to the improvements of the primary corridor, and (2) how the gains of a project, including congestion relief (e.g., delay reduction) and reduction of air pollution (e.g., emission of NOx), will evolve over time. These problems are very important for MassDOT to understand the full-scale of gains from the traffic flow improvements and then to identify suitable projects and leverage resources from CMAQ for Massachusetts.

The objective of this research is to conduct a synthesis study on the full-scale effects of TFI in terms of the influential region and the changes of gains over time. The ultimate goal is to inform MassDOT’s Office of Transportation Planning’s evaluation of CMAQ projects and their demonstrated benefits to relieve congestion and improve air quality.

This TFI Synthesis project consists of three main tasks: (1) a review of the commonly adopted TFI strategies and their impacts on traffic congestion mitigation and emission reduction; (2) a review of the methods for quantifying the effects of CMAQ TFI strategies; and (3) a survey of practitioners. The survey focuses on practitioners’ opinions about various TFI strategies, other promising TFI strategies not covered in the literature review, other TFI benefits quantification tools/methods not covered in the literature review, and how practitioners would rank different TFI strategies.

This report is divided into five chapters. The results of the above three tasks are described in Chapters 2, 3, and 4, respectively. Based on the literature review and the survey results, recommendations are provided in Chapter 5 for MassDOT to improve its CMAQ TFI program practices.

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2.0 Review of Traffic Flow Improvements Strategies

The purpose of this chapter is to identify commonly-used Traffic Flow Improvements (TFI) strategies and analyze their potential benefits and costs. The research team started with reviewing relevant TFI strategies that have been implemented in the U.S. by public agencies, to ensure that the identified strategies can have a reasonable chance to be successful in practice. Due to the limited number of qualified studies that have been identified, the team later expanded the review to include scientific research papers. This review is mainly based on the following sources:

1) FHWA Air Quality CMAQ Public Access System [1]: All states and the District of Columbia are required to log their CMAQ project obligations into these system each year. Although some of the reported projects have missing information (e.g., VOC Emissions Benefit), this public access system still provides valuable information for obtaining a comprehensive view of CMAQ TFI strategies that have been implemented in the U.S.
2) Air Quality and Congestion Mitigation Measure Outcomes Assessment Study: Final Technical Report [2].
3) SAFETEA-LU 1808: Congestion Mitigation and Air Quality Improvement Program Evaluation and Assessment – Phase 1 Final Report [3].
4) The Congestion Mitigation and Air Quality Improvement Program: Assessing 10 Years of Experience [4].
5) Other research papers found using Google and Google Scholar.

Based on the above sources, TFI strategies have been classified into the following categories. Categories 1 and 2 are for intersections (i.e., arterials), while Categories 3 and 4 are for roadway (both arterials and highways) segments. These strategies are further analyzed and the results are detailed in the rest of this chapter.

1) Category 1. Traffic Signalization
    a. Adding/upgrading a traffic signal and associated hardware investment
    b. Signal re-timing/synchronization and associated hardware investment
    c. Transit Signal Priority (TSP) and associated hardware investment

2) Category 2. Intersection Infrastructure Improvements
    a. Roundabouts (new or conversion into roundabout)
    b. All other intersection geometric improvements (e.g., adding curbs, medians, and turn bays, channelization, pavement resurfacing, grade separation)

3) Category 3. Highway Control and Management
    a. Managed lane (e.g., HOT, HOV, reversible, truck only lanes)

b. Highway/freeway management (variable speed limit, dynamic shoulder lane, ramp meter, other active traffic management strategies, investing in highway operations center, etc.)
c. Highway traveler information systems (e.g., dynamic message signs, time to destination display)

4) Category 4. Road Segment (including both highways and surface streets) Infrastructure Improvements
   a. Shoulder paving/widening
   b. Pavement resurfacing/rehabilitation
   c. Turn lane (i.e., shared left and right turn lane) and median construction (e.g., closing driveways and intersections)
   d. Ramp geometric improvements (e.g., extending an acceleration lane)

2.1 Analysis of TFI Strategy Benefits

A critical step to identify best TFI practices is to review the cost and benefits, particularly traffic emissions reduction and congestion mitigation effects, of each TFI strategy. The cost information is relatively easy to obtain. For traffic emissions reduction and congestion mitigation, they can be derived either through quantitative models (e.g., traffic simulation, dynamic traffic assignment) or by conducting before-and-after studies. Due to the high cost and time required for conducting before-and-after studies, most transportation agencies often do not choose this option unless it is really necessary.

In the CMAQ public access system [*1*], many reported projects do not have emissions reduction data provided. Even for those projects with emissions reduction data, many of them are derived using quantitative models or empirical estimates, not through before-and-after studies. Such information, particularly those from empirical estimates, sometimes is inaccurate and unreliable. Therefore, this research uses the CMAQ public access system data mainly for identifying a comprehensive list of TFI strategies. The benefits analysis of these TFI strategies is based on before-and-after study reports and other relevant quantitative studies identified by the team. The analysis of benefits is organized based on the TFI strategies listed in Section 1.

It is worth noting that when estimating TFI strategy benefits, transportation agencies often take parameters reflecting local or project conditions into consideration, such as typical trip lengths, temperatures, traffic compositions, vehicle speeds, and operating conditions [*3*]. Additionally, the estimated benefits depend on factors that are forecasted using sketch planning methods. These factors are often not validated by field data (e.g., post project evaluations). Therefore, the estimated TFI strategy benefits may not be directly applicable to Massachusetts. Nevertheless, they can be used as a reference for selecting TFI strategies for implementation.

Section 2.1.1 provides an overview of the TFI strategy benefits analysis. The remaining sections summarize the congestion and emissions benefits of the TFI strategies identified in this study by the following main categories.

1) Traffic Signalization
2) Intersection Infrastructure Improvements
3) Highway Control and Management
4) Road Segment Infrastructure Improvements

Typically evaluating the benefits of these strategies involves estimating/collecting traffic data (e.g. speed, VMT) before and after the TFI project, using such data to derive emissions factors, and multiplying these factors by VMT to estimate the total emissions benefits. In some studies, the emissions benefits are evaluated through estimating the vehicle delay reduction and multiplying it by an idle emissions factor measured in grams per hour. A few of these studies also takes traffic volume changes into consideration [*3*].

2.1.1 Overview of TFI Project Benefits

2.1.1.1 Direct and Indirect Impacts on Congestion Mitigation

TFI projects such as traffic signal retiming can directly improve the traffic operations at an intersection, reducing delay and number of stops. Such improvements may also indirectly benefit neighboring intersections and the entire roadway by preventing spillover and blockage of left/right turn bay, thus reducing travel time.

On the other hand, the reduced delay and travel time may attract travelers from other parallel routes, generate induced traffic demand for the subject intersection and neighboring ones. The induced demand will to some extent offset the congestion mitigation effects of the original TFI project. Eventually, an equilibrium state will be achieved, meaning no travelers can further reduce travel time by switching to the subject intersection. At this time, the benefits of the TFI project should consist of (1) delay reduction to vehicles that had been using this intersection previously; (2) delay reduction to vehicles that switched from other routes to the subject intersection; and (3) delay reduction to vehicles that had been using other routes and are still using those routes. Similarly, the improved traffic conditions for the parallel routes due to the TFI project will attract additional traffic from other areas. This rippling effect will be less significant and even more difficult to quantify.

For TFI projects that lead to very significant congestion mitigation, they may even attract travelers from other modes (e.g., transit, other non-motorized modes) or travelers who would otherwise not travel, although it is hard to distinguish such induced travel demand from those induced traffic demand discussed in the previous paragraph.

2.1.1.2 Direct and Indirect Impacts on Traffic Emissions

Similar to the congestion mitigation impacts, TFI projects can affect traffic emissions by either directly decreasing stop-and-go traffic and number of stops, or indirectly through their effects on induced travel and traffic demands. Sometimes, the indirect impacts can be negative. For example, reducing highway congestion may attract travelers from taking transit to driving, indirectly increasing traffic emissions. Therefore, it is important to evaluate a TFI project's overall (both direct and indirect) network traffic emissions impacts. In most cases, the indirect traffic emissions impacts are less significant and more difficult to quantify than the direct impacts, as it involves the modeling of traveler mode choice behavior.

2.1.1.3 Additional Considerations

When evaluating a TFI strategy's congestion and traffic emissions impacts, its *time of effectiveness* needs to be considered [*3*]. For example, managed lanes are typically well utilized on weekdays, but are often underutilized on weekends [*5*]. Also, dynamic shoulder lanes are enforced normally during rush hours on weekdays. Taking this time of effectiveness into consideration will help to avoid overestimating their benefits.

Another similar concept is *changes in effectiveness over time*. For all TFI projects, their benefits in general tend to change in the long term due to reasons such as (1) changes in traffic patterns (e.g., new patterns require traffic signal timing plans to be updated); (2) deterioration of infrastructure conditions (e.g., pavement conditions), (3) changes in travel behavior and demand (e.g., more trips provided by ridesharing like Uber, increased transit ridership), and (4) changes in vehicle technologies (e.g., more fuel-efficient engines) and traffic composition (e.g., more hybrid and electric vehicles). Even in the short term, the benefits are not constant. During off-peak hours, strategies such as managed lanes may be less effective compared to peak hours.

2.1.2 Traffic Signalization

Traffic signalization is probably the most widely-used strategy for improving traffic operations and reducing emissions, mainly because they are easy to deploy and are cost effective. In this study, traffic signalization is further divided into three sub-categories: adding/upgrading traffic signal and related hardware and software, signal re-timing/synchronization, and Transit Signal Priority (TSP).

2.1.2.1 Adding/Upgrading Traffic Signal and Related Hardware and Software

This subcategory includes projects such as converting stop-controlled intersections or roundabout into signalized intersections, upgrading pre-timed control to actuated control, adding new traffic sensors, etc. New traffic control systems in general are easier to maintain and can help to minimize system down time. Some systems even allow traffic engineers to remotely monitor their operations and update timing plans in real time.

Adding/upgrading traffic signals can help to reduce delay and number of stops. In most cases, this will reduce all types of traffic emissions such as VOC. However, travel speeds greater than 32 to 35 mph may increase CO and NO_x emissions [*3*]. Compared to signal re-timing strategies in Section 2.1.2.2, strategies in this subcategory are typically more expensive. Table 2.1 summarizes relevant studies identified in this research and their benefits (either estimated or measured).

2.1.2.2 Signal Re-Timing/Synchronization

Signal re-timing/synchronization is often a low-cost but highly effective strategy for mitigating congestion and reducing traffic emissions. There are about 300,000 traffic signals in the United States. It is recommended by the Institute of Transportation Engineers (ITE) that traffic signal timing plans be re-examined and retimed at least every 3 years [*6*]. Due to resource constraint, most transportation agencies exceed this recommended interval. It is estimated by the FHWA that the benefit-to-cost ratio for traffic signal timing optimization projects is 40:1, meaning for $1 spent, $40 benefits can be generated [*6*]. This subsection focuses on TFI projects that are related to traffic signal re-timing and associated hardware and software investment. The identified studies are summarized in Table 2.2.

Table 2.1: Mobility and Emissions Benefits and Cost for Adding/Upgrading Traffic Signal and Other Hardware

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits
Kentucky	$400,000	2005 (NA)	Install fiber optic cable for traffic signal control to reduce the system maintenance needs and avoid blocking traffic due to repairs. [*3*]	Reduce delay by 4 minutes per vehicle (based on the average delay reduction of 18 intersections) and 6,360 vehicle hours per day for the entire network	VOC - 33.5 kg/day CO – 378.0 kg/day NO_x – 9.1 kg/day Estimated based on EPA calculations for general vehicle fleet mix. The FHWA percentage of vehicle types was used to determine the grams of pollutant reduced per minute by the reduction in delay. (average of vehicle counts per arterial) * (minute of delay reduced by fiber optic) * (g/min per VOC, NOx, CO) = total grams VOC, NOx, CO per day

Table 2.2: Mobility and Emissions Benefits and Cost for Signal Re-Timing/Synchronization

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits	Benefit/cost ratio	Other Benefits
Michigan	$660,000	2002 (10)	Coordinate traffic signals along a 15-mile arterial [3]	VMT would not change and the average travel speeds for both AM and PM peaks would increase by 4 mph	VOC – 40.1 kg/day Emissions reductions calculated using Mobile 5a running emissions factors (g/mile) for VOC at the following speeds: Peak:31 mph: VOC = 1.843 35 mph: VOC = 1.697 Daily emissions reduced = (change in peak emissions * Peak VMT) + (change in off-peak emissions * Off-peak VMT)	--	--
Ohio	$639,543	2005 (5~10)	Turn four stop-controlled intersections into coordinated signalized intersections [3]	Synchro 5 was used. 702 hours of delay reduction each day.	VOC – 5.1 kg/day CO – 90.7 kg/day NO_x – 3.9 kg/day Emissions reductions calculated using Mobile6. Idle emissions calculated using exhaust emissions for a 2.5 mile/hour average speed.	--	--
Tennessee	$33,000	2005 (10)	Coordinate traffic signals along a 9.5-mile arterial [3]	Utilized "A Toolbox for Alleviating Traffic Congestion and Enhancing Mobility" by ITE [7] and estimated a speed increase of 4 mph (12%) from 34 to 38 mph	VOC – 15.0 kg/day NO_x + 2.2 kg/day Emissions factors before and after project implementation derived from MOBILE6. Emissions reduction = VMT * (Emissions Factor before - Emissions Factor after)	--	--

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits	Benefit/cost ratio	Other Benefits
Pennsylvania	$214,033	1994 (10)	Arterial Street Signal Interconnect [*8*]	--	VOC – 52.1 kg/day (19.0 ton/year) NO_x – 5.7 kg/day (9.1 ton/year)	--	--
Maryland	$6,295	2005 (12)	Signal Systemization Project along MD 2 [*8*]	--	VOC – 8.0 kg/day (2.92 ton/year)	--	--
Texas	$1,700,000	1995	Benefits for the Texas traffic light synchronization grant program [*9*]	Average delay – 19.4% # of stops – 8.8%.	Fuel consumption – 13.3%	38:1	--
California	--	2001	Develop and deploy adaptive signal control system at 375 intersections [*10*]	Average delay – 21% # of stops – 31% The benefits observed were much larger for two-phase intersections than multiple phases.	--	--	--
Missouri	--	2009	Evaluation of an Adaptive Traffic Signal System: Route 291 in Lee's Summit, Missouri [*11*]	Corridor travel time decreased by 0%~39%. The increase in delay to minor-street was less than the decrease in major-street delay.	HC – 6.2% ~ 40.7% CO – 4.3% ~ 28.9% NO_x – 8.8% ~ 50.0% The numbers vary when time of day or study location changes.	--	--
North Carolina	--	2000	Field evaluation of signal coordination on emission [*12*]	Travel time – 51% Average speed + 95%	Using field data collected by OEM-2100^{TM} from 824 runs (100 hours and 2,020 VMT) 35%~60% reductions for hydrocarbon (HC), CO, and NO_x	--	Reductions in delay and stops and improvements in LOS

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits	Benefit/cost ratio	Other Benefits
Arizona	--	2000	Field evaluation of signal coordination [*13*]	Average arterial speed + 6%; Number of stops – 3.6%	Based on field GPS trajectory data and statistical model: Fuel consumption – 1.6%; CO + 1.2%; No changes for HCs and NO_x	--	Crash risk – 6.7%
Michigan	--	2002	Signal retiming [*14*]	--	Based on field observations. Phase I Benefits: • CO – 2.5%; NO_x – 3.5%; HC – 4.2% Phase II Benefits: • CO – 1.7%; NO_x – 1.9%; HC – 2.7%	175:1 (Phase I) 55:1 (Phase II)	--
New York	--	--	Signal retiming [*14*]	# of stops – 15.7%; Delay – 18.8%; travel times – 16.7%;	Based on field observations, vehicle emissions – 13%	--	Fuel – 13.8% Noise – 13%
Germany	--	2010	Signal coordination [*15*]	--	10~40% emissions reductions based on Paramics simulation and VERSIT+	--	--
Illinois	$31,979	-- (20)	Signal Interconnection Project: Pulaski Rd from Stevenson Expy to 87th St, IL [*8*]	--	VOC – 20.82 kg/day (7.60 ton/year)	--	--
FHWA	--	1995	Improving Traffic Signal Operations: A Primer [*6*]	Speed without hardware improvements + 12% (+22% in some cases); Speed with signal coordination + 25%	--	40:1	Reduced fuel consumption, less stop-and-go traffic, and reduced rear-end crash risk

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits	Benefit/cost ratio	Other Benefits
Massachusetts	$2,242/signal	2010	The Benefits of Retiming/Rephasing Traffic Signals in the Back Bay [*16*]	Delay – 4.2 person hours/day/inter	Emissions – 0.34 kg/day/inter Did not specify emission types	47:1	– 0.044 crashes/inter/year; – 2.9 gallons/inter/day
ITE	--	2004	The benefits of retiming traffic signals. ITE journal [*17*]	Average based on the papers reviewed in [*17*] Time – 9.3% Delay – 36.8% Stops – 34.2%	--	60:1	Fuel – 6.57% Crash – 31%

In some of the studies summarized in Table 2.2 (e.g. [*12*]), the measured improvements are only for the arterial directions, and do not consider cross-street traffic. Also, an interesting finding in [*12*] is that "*emission rates are highest during acceleration and tend to decrease, in descending order, for cruise, deceleration, and idle*." Therefore, reducing number of stops (i.e., decelerations and accelerations) seems to be more important than reducing stopped delay (i.e., idling time).

2.1.2.3 Transit Signal Priority (TSP)

TSP gives higher priorities to transit vehicles and this can help to reduce the delay, stops, and emissions for them (see Table 2.3). However, its mobility and environment impacts on other vehicles may be negative. In a report [*18*] by ITS America, it is mentioned that the applications of TSP in England and France reduced transit travel time by 6 to 42%, but increased the travel time for other vehicles by 0.3 to 2.5%. For a 2-¼ mile segment in Cicero, IL, TSP was able to reduce transit travel time from 12 minutes to 8 minutes (33%). This report suggests that TSP has little or no negative impacts and sometimes positive impacts on the travel times of other vehicles along the transit routes, and the impacts on pedestrian delay are also negligible. However, this conclusion may not apply to the travel time of cross-street vehicles.

The same ITS America report mentioned that the cost for implementing TSP ranges between $8,000 and $35,000 per intersection, which depends on the system design and technologies used. This is significantly more expensive than the per intersection signal re-timing cost ($2,242 [*16*]).

2.1.3 Intersection Infrastructure Improvement

Intersection infrastructure improvement TFI strategies are different from traffic signalization TFIs (Section 2.1.2) in that they aim to improve traffic operations through changing the physical features of an intersection. Such TFI strategies include but are not limited to: adding curbs, medians, and turn bays, channelization, pavement resurfacing, and building roundabouts.

2.1.3.1 Roundabout

A roundabout is a type of traffic control strategy at intersections in which road traffic moves almost continuously in one direction around this central island. It requires entering traffic to give way to traffic already in the roundabout. Compared to other traffic control strategies, roundabouts have been proven to be able to reduce the likelihood and severity of collisions (see studies summarized in Table 2.4).

Table 2.3: Mobility and Emissions Benefits and Cost for Transit Signal Priority

Location	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits	Other
Virginia	2004	Implementing TSP along the Columbia Pike arterial corridor [*19*]	Arterial bus delay – 3.2% Cross bus delay – 10.5% The negative impacts to overall system is negligible when V/C ratio is under 0.8	The emissions difference is insignificant in this before-and-after study	--
Minnesota	2006	Investigate the impacts of TSP along the Franklin Corridor (22 intersections) by AIMSUM simulation [*20*]	AM transit delay – 16~20% PM transit delay – 5~14% For non-transit traffic delay, + 6 sec/veh and + 22 sec/veh for AM and PM peak hours, respectively. For overall traffic, + 7 sec/veh and 0.1 stop/veh for AM peak (+ 23 sec/veh and 0.6 stop/vehicle for PM)	--	--
Washington	2008	Evaluate the impacts of South Snohomish Regional Transit Signal Priority (SS-RTSP) project on basis of field-observed data. [*21*]	Simulation was conducted to obtain the measure of effectiveness that was not available from field data. Transit travel time – 4.9% Corridor delay – 56,227 person-hours/year for peak-hour only For local traffic delay, the changes were found to be insignificant.	--	--
California	2013	Study the emissions impact of phase insertion TSP strategy on corridor network of EI Camino Real, CA by Paramics simulation [*22*]	--	Transit emissions were reduced. The emission from overall traffic increased by 11%. Transit emissions in AM peak: CO – 9.28%; CO_2 – 9.13%; HC – 11.45%; NO_x – 10.78%; Fuel – 9.13% All traffic emission in AM peak: CO +14.22%; CO_2 +12.32%; HC + 13.58%; NO_x + 5.61%; Fuel + 12.36%	--

Oregon	1996	Lewis, V. (1996). Bus Priority Study: Tualatin Valley Highway. Tri-Met, Portland, OR. [*18*,*23*]	Bus travel time – 1.4~6.4% Average bus signal delay – 20%	--	--
Washington	1999	Preliminary Transit Signal Priority Assessment of S. Genesee Street and Rainier Avenue South. Seattle, WA, 1999. [*18*,*24*]	Signal related stops for bus – 50% Signal related delay for bus – 57% Intersection average person delay – 13.5% Average intersection delay did not change for traffic Bus travel time variability – 35% Side street effects were insignificant	--	--
Europe	1995	Traffic Control Systems Give Transit a Break [*18*]	Transit signal delay – 10 sec/inter Potential transit signal delay – 40~80% Transit travel time – 6~42% in England and France 1~2 year payback period for installation of TSP	--	0.3~2.5% increase in auto travel times
Washington	2000	Transit Signal Priority System Assessment Study [*18*,*25*]	Stops for buses – 24% Bus travel time – 8% Bus delay – 34%	--	--
Oregon	1994	Powell Blvd. Bus Signal Priority Pilot Project Final Report. Portland, OR [*18*,*26*]	Bus travel time – 5~8% Bus person delay had a general decrease	--	Inconclusive impacts of TSP on other traffic
Japan	1996	ITS Developed by Japanese Police [*18*]	Bus travel time – 6.1% Bus stops – 7.1% Bus stopped time – 20.8%	--	9.9% increase in ridership
Canada	2000	Transit Signal Priority: A Comparison of Recent and Future Implementations [*18*,*27*]	Transit signal delay – 15~49%	--	1 street car removed from service

Illinois	1998	The Cermak Road Bus Priority Project Final Report. Chicago, IL, 1998 [*18*,*28*]	7~20% reduction in transit travel time depending on time of day and travel direction 1.5 sec/veh average decrease in delay (range: +1.1 to –7.8) 8.2 sec/veh average increase in cross-street delay (range: +0.4 to +37.9) Transit schedule reliability improved	--	• **Reduced number of buses needed to operate the service** • Passenger satisfaction level increased
California		Transit Preferential Streets Program in San Francisco [*18*,*29*]	Transit signal delay – 6~25%	--	--
Minnesota		Signal Priority for Buses: An Operational Test at Louisiana Avenue, Minneapolis [*18*,*30*]	0~38% reduction in bus travel times depending on TSP strategy **23% (4.4 sec/veh) increase in traffic delay**		Skipping signal phases **caused driver frustration**

Table 2.4: Mobility and Emissions Benefits and Cost for Roundabout

Location	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits
New York	2007 (NA)	A $4.87 million project to convert a signalized intersection into a two-lane roundabout (with sidewalks) [*3*]	Utilized the CDTC STEP Model [*31*] to estimate delay for the existing condition. The RODEL [*32*] Roundabout Capacity Model was used to estimate the delay reduction. Average speed + 14 mph (from 15 to 29, 93.3%) Average delay – 6.5 sec/veh (11.5 to 5, 56.5%).	VOC – 24.2 kg/day NO_x – 1.9 kg/day CO – 24.2 kg/day The NYSDOT software package CMAQtraq was used. Effects were calculated for 250 days/year with the following emissions factors (g/mile): CO = Before: 18.01 After: 16.02 VOC = Before: 1.01 After: 0.71 NOx = Before: 0.95 After: 0.79
Kansas	2005	Operational performance of Kansas roundabouts: phase II [*33*]	Based on data from 5 locations in Kansas. Maximum delay reduced from 34.4 seconds to 8.0 seconds, and average intersection delay was reduced from 20.2 seconds to 10.4 seconds. The 95% queue length decreased from 195 feet to 104 feet. The proportion of vehicles stopped reduced by 50%, while the maximum proportion of vehicle stopped reduced by 42%.	--
Kansas and Nevada	2003	Study the impact of modern roundabout in cutting down emissions in 6 locations (previous controlled by stop signs) with different traffic volumes [*34*]	--	The base cases are All Way Stop Control or Two Way Stop Control. SIDRA 2.0 was used to calculate emission MOEs. All the emission reduction results are statistically significant. AM peak hours: CO: –21%; CO_2: –16%; NO_x: –20%; HC: –18% PM peak hours: CO: –42%; CO_2: –59%; NO_x: –48%; HC: –65%

Location	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits
Sweden	2001	Evaluation of the small roundabouts' effect on emissions and fuel consumption [*35*]	--	A "car-following" method was used in this before/after study. When The base case was a signalized intersection, the reductions are: CO –29%; NO_x –21%; Fuel –28% When the base case was yield regulated intersection, the reductions are: CO +4%; NO_x +6%; Fuel +3%
North Carolina	2015	Compare the emissions generated from roundabouts and signalized intersections based on a macroscopic method with vehicle trajectories data collected from 6 U.S. states [*36*]	--	When V/C<=0.7, roundabouts generate lower emission rates than signal control. When the V/C ratio>0.7, the signal control emission rates are lower given proper timing plans. When V/C>1, roundabouts generate consistently higher emission rates than signal control.
Italy	2017	A before-and-after study on emission under signal and roundabout control. Portable Emission Measurement Systems (PEMS) used to collect emission data directly (a total of 396 trips) [*37*].	--	Compared to signal control, roundabout reduces CO_2 in most cases, but **increases** NO_x. The difference in terms of CO is statistically insignificant.

2.1.3.2 Other Geometric Improvements

Much less literatures have been identified for other intersection geometric improvements (e.g., adding medians, grade separation, adding turn bays) than for constructing roundabouts. These strategies are summarized in Table 2.5.

2.1.4 Highway Control and Management

2.1.4.1 Managed Lanes

Managed lanes such as HOV and HOT lanes can improve mobility and reduce traffic emissions through: (1) encouraging travelers to carpool and reduce total VMT and number of vehicles; (2) allowing faster speeds for managed lane users and potentially general-purpose lane users as well. Also, some managed lane facilities are open to the general traffic without any restrictions during off-peak periods (such as the HOV lane on I-93). This can increase the overall capacity if the managed lane facility was not built by taking the existing general-purpose lane(s). Compared to traffic signalization projects, managed lane projects are usually much more expensive. However, like other infrastructure improvement projects, their corresponding mobility and emissions benefits typically last longer.

Crawford et al. [*38*] reviewed a number of congestion mitigation strategies and found that adding HOV lanes can help to significantly increase transit and carpooling users. HOV lanes were also found to increase vehicle occupancy and person throughput [*2*,*39*,*40*,*41*,*42*]. These factors all contribute to reduced vehicle trips, VMT, traffic emissions, and congestion [*2*,*39*,*62*,*43*,*44*].

The extra capacity offered by managed lanes can be utilized to mitigate the congestion on the general-purpose lanes [*2*,*40*,*45*,*46*,*47*]. By dynamically changing the toll rate according to traffic conditions, managed lanes (HOT) can help to reduce travel time and increase travel time reliability. [*2*,*48*,*49*]. For example, the Katy Managed Lanes in Houston can save travel time by 5 to 15 minutes [*2*,*50*].

Shi and Yu [*51*] used a Portable Emission Measurement System (PEMS) and a testing vehicle to measure the emission reduction effects of HOV lanes. Their concluded that "without the consideration of the effect of HOV lane on VMT, the emission reduction rate on the first testing day is 3.56 percent, and due to an increased traffic demand on the corresponding mixed-flow lane on the second testing day, the emission reduction rate by using HOV lane increased to 10.42 percent."

The relevant managed lane studies are further summarized in Table 2.6.

Table 2.5: Mobility and Emissions Benefits and Cost for Other Geometric Improvements

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits
Louisiana	$5.5 M	2004 (10)	Convert an intersection into a Continuous Flow Intersection (CFI) [*3*,*52*]	VISSIM was used to analyze the benefits. Project would increase the flow from 5,800 to 6,500 vph in the AM peak, and from 6,200 to 6,700 vph in the PM peak It would decrease the average delay from 92.6 to 36.0 sec/veh (-61.1%) in AM, and 178.3 to 34.4 sec/veh (-80.7%) in PM. Given that VISSIM was used in the analysis, the increase in flow was probably due to the oversaturated current traffic condition, not through an induced demand analysis	VOC – 20.1 kg/day; NO_x – 5.2 kg/day Emissions reductions calculated from changes in delay based on MOBILE6, using 2.5 mph speed, and converted into idle emissions factors. Emissions factor for VOC = 10.35 g/mi; Emissions factor for NOX= 2.67 g/mi Reduction = Delay in vehicle-hours/hour * Emissions Factor * 2.5 (conversion of gm/mi to gm/hr) * 2 hours for each peak period
Kentucky	$500,000	2006 (10)	Add reversible lane controls [*3*,*53*,*54*,*55*]	Based on a 1-hour Synchro simulation, the delay reduction was estimated to be 63 vehicle-hours (17%).	VOC – 2.9 kg/day; NO_x – 1.1 kg/day; CO – 45.0 kg/day The delay reductions were used to calculate the emissions savings using emissions factors provided by EPA Office of Transportation and Air Quality. Reduction in delay * average of vehicle mix for kg/min per CO, NO_x, VOC * 255 days per year.
Netherlands	--	2008	Emissions impact of 5 intersection designs [*2*,*56*]	--	Ground level intersections generated about 39.4% and 34% more NO_x and PM_{10} emissions, respectively, than grade separated intersections.
Melbourne	--	2010	Before and after study for grade-separated crossing in Melbourne [*57*]	Daily traffic volumes increased by 8% on the grade-separated road (18% for AM and 15% for PM peak). Daily traffic volumes decreased on parallel (competing) roads by 6% (11-13% for AM and 8-9% for PM). Travel time decreased up to 22% in peak periods.	--

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits
Montana	--	2014	2016 Montana Rail Grade Separation Study Final Report [*58*]	Identified 10 out of 5,200 at-grade intersections. Grade separation BC analyses are conducted for these intersection. Only three of them have a BC ratio greater than 0.2 (0.22, 1.05, and 0.45). It appears that overpass is twice more cost effective than underpass. Potential benefits include: travel time reduction, improved safety, vehicle operating cost saving, O&M cost, and reduced pavement damage.	Reduced environment costs (vary depending on projects). More details can be found in the report. This project did consider the impact over the next 20 years.
California	--	2012	Grade separation on 7th Street the Port of Oakland. [*59*]	Compared 2012 to 2002, 6,820 fewer daily trips than 2002 (1,410 trips during AM peak and 1,220 in PM peak). Intersection delay reduced from 100.7 second per vehicle to 75.9 seconds per vehicle (24.6%).	--
Washington	--	2015	Lander Street Grade Separation Transportation Discipline Report [*60*]	Estimated (using SimTraffic) travel time reduction 252 seconds (4.2 minutes) during AM peak and 214 seconds (3.6 minutes) during PM peak. The reductions in delay and travel time range from about 60% during the midday hours to 81% during the PM peak hour	--

Table 2.6: Mobility and Emissions Benefits and Cost for Managed Lane

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits
Texas	$254,570,093	2002 (20)	Construct an HOV Interchange at IH635 and US75 in Dallas [*3*].	• Assumed HOV users per day is 10053.72 and the average vehicle occupancy of rideshares is 2.14 persons per vehicle. Also assumed the percentages of people attracted to the HOV from other modes. • Calculate daily vehicle trip reduction • Calculate VMT reduction = trips reduced * 20 miles average auto trip length. • Reduce 2,929 vehicle trips/day and 58,589 VMT per day.	VOC – 68.78 kg/day NO_x – 135.32 kg/day Emissions reductions calculated using Mobile6 running emissions factors. Made assumptions about running speed on freeways before the project, volumes of the HOV and general purpose lanes.
Connecticut	$1,435,894	-- (20)	Extension of HOV Lanes on Interstate 84 from East Hartford to Hartford, CT [*8*]	--	VOC: - 9.04 kg/day (- 3.3 ton/year) NOx: -3.01 kg/day (- 1.1 ton/year)
California	--	1991	Implementation of an HOV lane on I-15 in San Diego in 1988 [*61*]	--	Reduced CO by 25% based on user mile from the 1988 level. The 1990 CO emissions would be 65% greater if the HOV lane had not been constructed.
California	--	2007	The operational differences in traffic dynamics between HOV lanes and mixed-flow (MF) [*62*] lanes, and their impacts on emissions.	On congested freeways, HOV lanes provide travel time saving of 2.75 minutes/mile to carpoolers. On uncongested freeways, the benefits are negligible.	On congested freeways, HOV lanes produce 10-15% less HC and NO_x, and 35% less CO_2 and fuel consumption rates than MF lanes. On uncongested freeways, the emissions mass on a per lane basis for HOV lanes is still lower.

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits
California	--	2008	Estimate and compare vehicle emissions contributed from continuous access HOV lanes and limited access HOV lanes by integrating a microscopic simulation software PARAMICS with a modal emissions model CMEM [*63*].	The operational measure is defined as Q, which is the ratio of VMT to VHT (vehicle hours traveled). The higher the Q, the better the traffic conditions. It is found the Q value for continuous access HOV is about 4-6 mph higher compared to limited access HOV.	The limited access HOV lanes introduce more emissions because of more frequent and aggressive acceleration/deceleration maneuvers at assigned ingress/egress sections. The difference ranges from 17-25% based on different scenarios.
Texas	--	2002	Investigate the operational effectiveness of the Dallas area HOV lanes [*64*]	The project had no negative impact on the general-purpose lane speed. The observed HOV lane speed was significantly higher than the general-purpose lane speed. The HOV lane saved motorists more than 5 minutes than the general-purpose lanes, the corresponding perceived saving was 12-16 minutes in peak hours.	VOC – 23.3 kg/day (51.4 lbs/day) on IH-35E North VOC – 107.4 kg/day (236.7 lbs/day) on IH-635

2.1.4.2 Highway/Freeway Management

Highway/freeway management TFI projects aim to improve traffic flow along major highways particularly during rush hours and incident conditions. These projects may include providing service patrols to assist disabled vehicles, incident detection and response system, and active traffic management. Such strategies can have significant impacts on congestion mitigation and emission reduction. In particular, traffic incidents contribute to approximate 25% of all traffic delays. Prompt incident response and clearance can generate substantial mobility, environment, and safety benefits. The following summarizes some of the studies reviewed. A complete list of the reviewed highway/freeway management studies are in Table 2.7.

2.1.4.3 Highway Traveler Information Systems

Traveler Information System (TIS) provide travelers with both static and real-time traffic related information for them to make informed pre-trip (e.g., departure time, mode choice) and en-route decisions (e.g., re-routing). TIS is particularly important for mitigating congestion and reducing traffic emissions during traffic incidents and hazardous weather conditions. As summarized in Table 2.8, it can reduce emissions and mitigate congestion by affecting driving behavior (i.e., reducing unnecessary accelerations and braking) and promoting public transit (i.e., reducing VMT and vehicle cold starts).

It is pointed out in [*2*] that "*Most of the emissions impacts found in the available literature resulting from implementation of ATIS come from the reduction in VMT, fuel use from acceleration/deceleration, cold starts, and idling. However, one study using the SCRITS analysis tool indicated that traveler information programs may cause an increase in VMT (due to shifting to longer but faster routes) that roughly offsets the emissions benefits from reduced delay on the mainline*".

2.1.5 Road Segment Infrastructure Improvements

Road segment infrastructure improvements include shoulder paving/widening, pavement resurfacing/rehabilitation, turn lane and median construction, and ramp geometric improvements. Since most road segment infrastructure improvements studies only document safety benefits, our review generates very limited before-and-after information for the mobility and emission benefits. Therefore, these TFI strategies are not analyzed individually as in previous sections and are summarized in Table 2.9.

Table 2.7: Mobility and Emissions Benefits and Cost for Highway/Freeway Management

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits
Louisiana	$2,712,940	2003 (10)	Install ITS devices along I-10 from Acadian St. to Highland Blvd. for improved incident response [*3*]	Assumed that VMT and vehicle trips would not be affected, and the main benefits would be traffic emissions reduction.	VOC – 189.6 kg/day; NOx – 489.0 kg/day Assumed running speed of 40 mph. ***Freeway emissions*** = freeway VMT (from Tranplan model) * Emissions factor (from MOBILE in grams/mile) ***Freeway emissions due to nonrecurring congestion*** = freeway emissions * 0.049 (assumes 4.9% of freeway emissions are caused by nonrecurring congestion [*65*]. ***Emissions reduced due to program*** = freeway emissions due to nonrecurring congestion * effectiveness factor.
Washington	$2.0 M	2004 (10)	Install ITS devices along a freeway [*3*] including communication devices among traffic signals, controller upgrading, variable message signs and other driver information systems, new traffic control strategies, and CCTV and roadway signs for traffic monitoring.	Increase travel speed by 2 mph (10.5%) during AM and PM peak periods	VOC – 76 kg/day NOx – 4 kg/day CO – 939 kg/day Calculated using the TCM Tools program created by Parsons Brinkerhoff and Sierra Research in 1994, which applies project data to the project year's (2004) MOBILE emissions factors and regional data.

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits
Connecticut	$1,421,384	2005 (10)	Install an incident management system along a 14-mile segment on I-95 [*3*], including installing a fiber-optic communication system, video surveillance, traffic flow monitors, etc.	Save 1.72 million vehicle hours per year (or 23,561 vehicle miles traveled)	VOC – 6.11 kg/day NOx – 3 kg/day $PM_{2.5}$ – 0.004 kg/day
Alabama	$800,000	2007 (1)	Provides free services to disabled vehicles from 6 am to 10 pm to reduce response time [*3*]	3,849 vehicle hours per incidents Incident Delay = Traffic volume * (Average number of blocked lanes during incidents / total lanes in corridor) * Incident duration Change in delay = Incident delay without project - Incident delay with project	VOC – 31.25 kg/day NOx – 11.88 kg/day $PM_{2.5}$ – 0.12 kg/day For each pollutant, the Change in delay * Emissions Factor / 1,000 * 111 annual incidents / 260 working days = kg of emissions reduced per day
Georgia	$841,309	2010 (10)	Incident Management Program/ATMS [*8*]	--	VOC – 452.05 kg/day (165 ton/year) NOx – 432.88 kg/day (158 ton/year)
FHWA	--	1999	Impact analysis of ATIS, ATMS, and Incident Management Systems [*66*]	All the following are statistically significant Delay – 7% Throughput +0.2% Trip Time Variation – 2.1% VMT +0.4% Number of stops – 2.7%	All the following are statistically in significant Fuel +0.3% HC +0.5% CO +1.0% NOx +0.5%

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits
Texas	$27,428,052	2000	Metropolitan Model Deployment Initiative: San Antonio Evaluation Report [*69*]	For the freeway management component: Incident delay reduced 5.7% for all travelers. Secondary crash risk reduced 2.8% for all travelers. For all: Fuel reduced 1.2%	

Table 2.8: Mobility and Emissions Benefits and Cost for Highway Traveler Information System

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits	Other Benefits
Georgia	$140 million	--	NAVIGATOR multimodal TIS system. This project includes ramp meters, signal coordination, VMS, and information kiosks [*67*].	GDOT estimates that the incident management components of NAVIGATOR reduced the average incident duration by 23 minutes (from 64 mins to 41 mins), delay on highways by 3.2 million hours per year (1.3 million hours for AM peak and 1.9 million hours for PM peak), and a cost savings of $45 million per year.	VOC – 614 kg/day NO_x – 578 kg/day No mentioning of how these benefits were calculated	Improve safety and more efficient use of emergency services
FHWA	--	1999	Impact analysis of ATIS, ATMS, and Incident Management Systems [*66*]	NS - statistically insignificant Delay – 1.5% Throughput 0.0% (NS) Trip Time Variation – 2.5% VMT – 0.1%(NS) # of stops + 0.1%(NS)	The following are for ATIS and are all statistically in significant Fuel consumption – 0.1% (NS) HC – 0.1% (NS) CO – 0.3% (NS) NO_x – 0.3% (NS)	--
New York	--	2011	Environmental Benefits of a Statewide Traffic Video Network [*68*]	--	It was estimated that the changes in travel behavior due to ATIS prior to travel can generate a one-day net reduction of 71 kg/day of VOC, 4 kg/day of NO_x and 767 kg/day of CO.	Reduced energy consumption through reduced idling in congestion and increased transit ridership.

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits	Other Benefits
Texas	$31,701	2000	Metropolitan Model Deployment Initiative: San Antonio Evaluation Report [*69*]	Travelers who use the web site prior to traveling along a particular corridor would receive annual benefits of a 5.4% reduction in delay, a 0.5% reduction in crash rate, and a 1.8% reduction in fuel consumption.	--	--
California	--	2006	An automated work zone information system (AWIS) enabled travelers to observe traffic conditions before they entered the work zone and choose alternate routes based on guidance from DMS [*70*]	• ADT on I-15S decreased by 19% while ADT on I-215S (detour route) increased by 15%. • ADT on I-15N decreased by 16% while ADT on I-10E (detour route) increased by 10%. • ADT volumes on the adjacent major arterials increased by only 2%. • Field data indicated that the maximum average peak delay with AWIS was 50% less than the expected maximum delay without it.	--	--

Table 2.9: Mobility and Emissions Benefits and Cost for Road Segment Infrastructure Improvements

Location	Total Cost	Year (Project Life)	Project Description	Mobility Benefits	Emissions Benefits
Netherlands	--	2008	Modeled the emissions impact for NOx and PM10 of 5 intersection designs [*2*,*71*]	--	Ground level intersections generated about 39.4% and 34% more NOx and PM10 emissions, respectively than grade separated intersections.
Arizona	--	2014	PM-10 Paving Unpaved Road Projects for PM-10 Emission Reductions [*72*]	No impacts on NOx, VOC, and CO	PM-10 reduction effectiveness: Paving dirt roads: $775/ton Paving dirt alleys: $10,284/ton Paving dirt roads: $3,501/ton Paving dirt roads: $16,934/ton
California	$24,000,000	2014	Analyzed the tradeoffs between costs and emissions for road resurfacing [*73*]	--	A new policy would save 3,600 metric tons CO_2/year (14% reduction) and $0.6 million/year (2.5% reduction) in total costs.

2.2 Comparison and Conclusions

Based on the review results, the following conclusions are drawn:

1. Different performance measures are used in existing studies, such as % reduction, kg/day, tons/year, mph, and benefit/cost ratio. Some studies provide project cost information, while many others do not. The scopes of different projects and the assumptions made in benefit quantification are very different. All these make it difficult to have a quantitative comparison of the cost-effectiveness of various TFI strategies and rank them. Therefore, a qualitative comparison of the identified strategies are presented in Table 2.10. The number of black circles in the "Cost" column of Table 2.10 indicates how costly a particular strategy is. More black circles mean more expensive. Similarly, more black circles in the "Cost-effectiveness" column suggest more cost effective.
2. The quantitative results from the reviewed studies, although sometimes vary significantly from one study to another, are still useful. In general, capital projects are more expensive (e.g., several million dollars), while projects focusing on management strategies are less expensive (e.g., signal re-timing costs about $2,242/intersection [*16*]). Sometimes, it is difficult to draw a clear line between capital projects and management projects. For example, some signal re-timing projects may also require hardware and software upgrades.
3. Although management strategies are less expensive (and appear to be more cost effective), they can be effective only for certain traffic demand ranges. When the demand is too high, capital improvements in most cases will become increasingly necessary.
4. The benefits reported in previous studies (whether estimated or observed) should be considered as rough estimates, since there are many location-dependent variables involved. For example, some very significant performance improvements after a signal re-timing project could be largely attributed to the very poor signal timing plans used before. Applying the same strategy to a different location could generate marginal performance improvements. Therefore, the selection of TFI strategies should be analyzed on a case-by-case basis, although the idea to have an unambiguous ranking of all TFI strategies is appealing.
5. Most studies did not consider the changes of the benefits over time (e.g., a 10-year period) and only analyzed the impacts for a specific year. Also, most of the studies did not include a detailed analysis of traffic redistribution as a result of the project. Some studies utilized transportation planning models in estimating future traffic volumes, which is a reasonable approach but requires considerable time and efforts.
6. To evaluate a TFI project's long-term impacts, it would be important to take into consideration changes in (1) traffic patterns (e.g., new patterns require traffic signal timing plans to be updated); (2) deterioration of infrastructure conditions (e.g., pavement conditions), (3) travel behavior and demand (e.g., more trips

provided by ridesharing like Uber, increased transit ridership), and (4) vehicle technologies (e.g., more fuel-efficient engines) and traffic composition (e.g., more hybrid and electric vehicles).

7. Very few studies evaluated the PM emissions benefits of TFI projects. This could be partially due to the fact that "*EPA's MOBILE6 model does not account for the effects of changes in vehicle operating speeds on PM emissions, one would expect no reportable change in PM emissions for projects that alter vehicle operating speeds*." [*3*]

Although it is a very challenging task, Puckett et al. [*74*] did manage to complete a quantitative cost-effectiveness analysis of CMAQ strategies, which were measured in terms of dollars per short ton of CO, NO_x, VOC, PM_{10}, and $PM_{2.5}$ reduced. EPA's MOVES2010b model was utilized to estimate the emission reductions. As shown in Figure 2.1, the study by Puckett et al. is not specifically for TFI strategies, and only *Intersection Improvement*, *Roundabouts*, and *Incident Management* are related to our research.

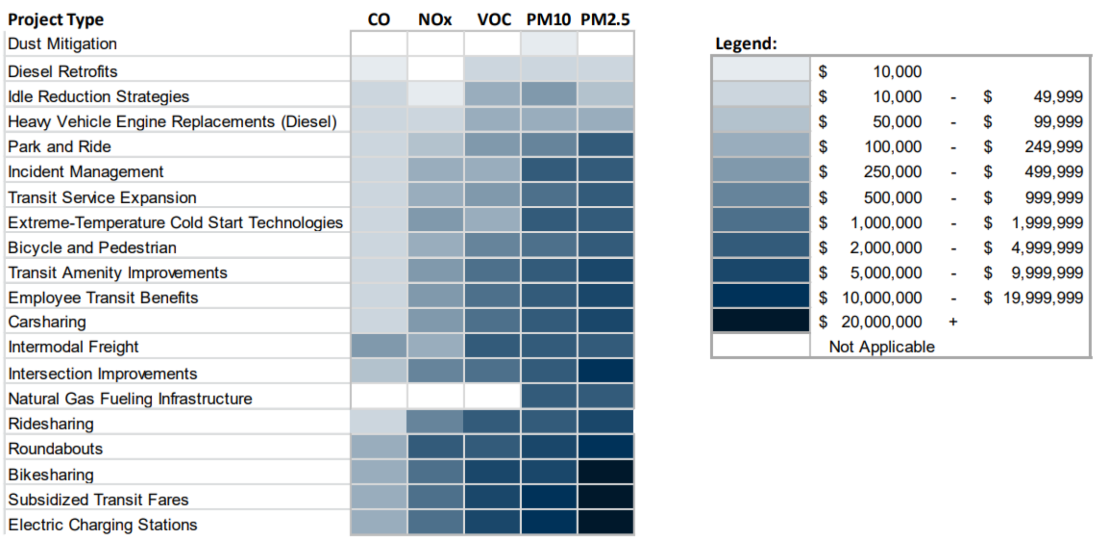

Figure 2.1: Median Cost-Effectiveness estimates for CMAQ Projects [*74*]

From Figure 2.1, *Incident Management* is very cost-effective in reducing CO and VOC, and moderately cost-effective for reducing NO_x. However, it is much less effective in reducing PM_{10}, and $PM_{2.5}$. *Intersection Improvements* have reasonably good reduction performance for CO, NO_x, and VOC, but not for PM_{10} and $PM_{2.5}$. *Roundabouts* have comparable performance as *Intersection Improvements*, but are slightly less effective in terms of all measures. Although the results are interesting, this study has two main limitations:

2. The emission impacts in different years over the project lifetime were not discounted and constant annual impacts were assumed.
3. For comparison across project type, only the median cost-effectiveness estimates are presented.

In another study, the National Research Council (NRC) [*4*] assessed the cost-effectiveness of Transportation Control Measures (TCMs) eligible for CMAQ funding. The cost-effectiveness was measured based on the cost for reducing one ton of overall weighted pollutants, which is similar to the criterion used in the study by Puckett et al. When calculating the cost-effectiveness, the weights for VOC and NO_x are set to 1 and 4, respectively. The results are presented in Figures 2.2 and 2.3. Among the strategies evaluated, only *HOV facilities, freeway/incident management*, and *traffic signalization* are related to this research. As can be seen from these two figures, the most cost-effective strategy is traffic signalization. Based on the median value, traffic signalization is 9.9 and 5.7 times more cost effective than HOV facilities and freeway management, respectively.

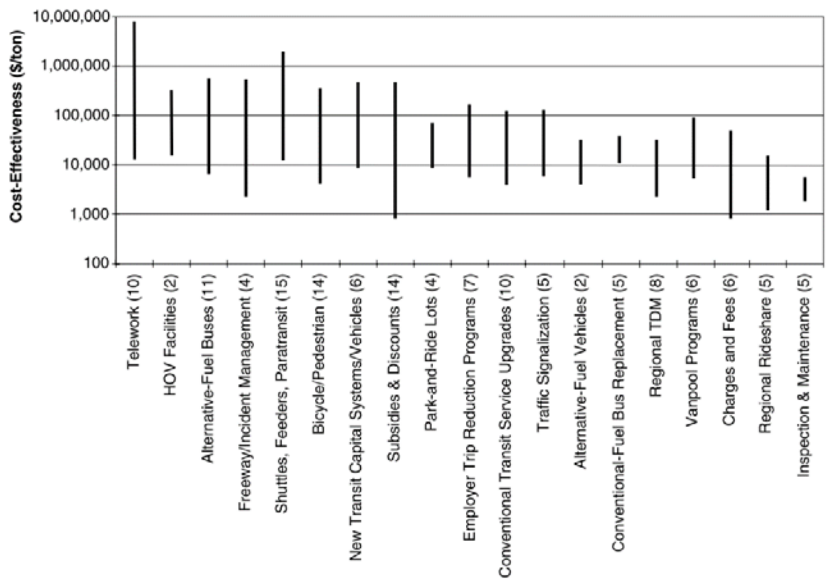

Figure 2.2: Range of Cost-Effectiveness Results for CMAQ-Eligible Strategies. [*4*]

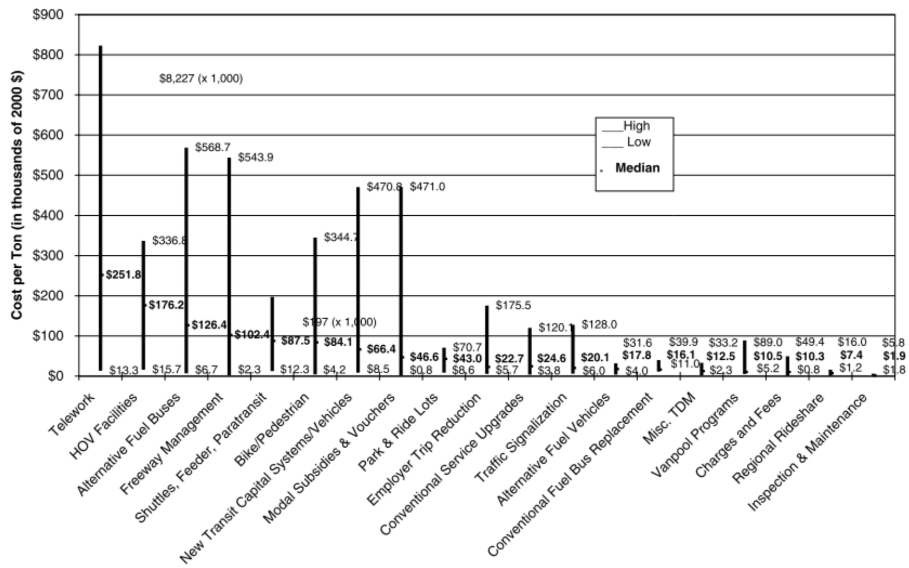

Figure 2.3: Cost-Effectiveness Range of Strategies (high/low range and median). [*4*]

Table 2.10: Qualitative Comparison of Different TFI Strategies

Strategy	Cost	Cost-Effectiveness	Service Lifespan	Area	Mobility Benefits	Emissions Benefits	Other
Adding/ Upgrading Traffic Signal	●●●○○[2]	●●●○○[2]	10-15 years	Spot	• Reduce delay and number of stops • Improve capacity	• Reduce all types of emissions	• Separate conflicting movements and reduce angle crash risk • **Increase** rear-end crash risk • Reduce fuel consumption
Signal Re-timing/ Synchronization	●●○○○[1]	●●●●●[2]	3 years	Spot/ corridor	• Reduce delay and number of stops • The average speed would increase significantly if synchronization is implemented	• Reduce all types of emissions	• Synchronization reduces rear-end crash risk and further reduces emissions • Reduce fuel consumption
Transit Signal Priority (TSP)	●●●○○[2]	●●○○○[2]	10-15 years	Spot/ corridor	• Reduce bus delay and stops • May **increase** delay to other traffic	• Reduce all types of emissions for buses • May **increase** emissions to other traffic	• Cause **frustration** to other drivers • Provide same service with less buses • Increase transit ridership • Improve transit service reliability

Strategy	Cost	Cost-Effectiveness	Service Lifespan	Area	Mobility Benefits	Emissions Benefits	Other
Roundabouts	●●●●○[1]	●●○○○[2]	25 years	Spot	• Reduce delay and stops	• Reduce all types of emissions	• Improve safety • Pedestrian and cyclist **unfriendly** • Reduce fuel consumption • Not suitable under heavy circulatory flow
Other Intersection Geometric Improvements	●●●○○[2]	●●●○○[2]	15-25 years	Spot	• Reduce delay and stops	• Reduce all types of emissions	• Reduce fuel consumption • Improve safety
Managed Lane	●●●●●[1]	●●○○○[2]	25 years	Corridor	• Reduce travel time for HOV lane users	• HOV lanes generate much less emissions than mixed traffic lanes	• May **add** additional traffic delay to general-purpose lanes • Increase vehicle occupancy • HOT may generate additional revenue
Highway/ Freeway Management	●●●●○[1]	●●●○○[2]	10-15 years	Corridor/ Region	• Reduce delay and stop-and-go traffic • Improve traffic flow and reduce shockwaves	• Reduce all types of emissions	• Improve safety
Highway Traveler Information Systems	●●○○○[1]	●●●○○[2]	10-15 years	Corridor/ Region	• Reduce VMT and delay	• Reduce all types of emissions	• Improve safety • Increase transit ridership

Strategy	Cost	Cost-Effectiveness	Service Lifespan	Area	Mobility Benefits	Emissions Benefits	Other
Shoulder Paving/ Widening	●●○○○[1]	●●●○○[2]	15-25 years	Corridor	• Reduce delay • Increase capacity	• Reduce all types of emissions	• Usually used during peak hours • May **increase** safety risk
Pavement Resurfacing/ Rehabilitation	●●●○○[2]	●○○○○[2]	15-25 years	Corridor	• May increase capacity and reduce delay	• May reduce all types of emissions	• Improve safety • Improve driving experience
Turn Lane and Median Construction	●●●●○[1]	●●○○○[2]	15-25 years	Corridor	• Increase capacity • Reduce delay and stops	• May reduce all types of emissions	• Improve safety by reducing conflicts
Ramp Geometric Improvements	●●●○○[1]	●●○○○[2]	15-25 years	Spot	• Improve traffic flow stability by reducing crash risk	• My reduce emissions by reducing crash risk	• Main contribution is to improve safety

[1] based on TTI Website https://mobility.tamu.edu/mip/strategies.php. The number of black circles in the “Cost” column indicates how costly a particular strategy is. Similarly, more black circles in the “Cost-effectiveness” column suggest more cost effective.
[2] based on information from [*4*,*74*] and other studies reviewed in this research. The number of black circles in the “Cost” column of indicates how costly a particular strategy is. Similarly, more black circles in the “Cost-effectiveness” column suggest more cost effective.

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3.0 Review of TFI Strategy Quantification Methods

Based on the literature review, the methods used for quantifying the mobility and air quality impacts of CMAQ TFI strategies can largely be classified into three categories: (1) sketch planning methods, (2) computer simulation, and (3) before-and-after studies. This report is therefore structured following this classification. In the remaining part of this chapter, an overview of various quantification methods is presented in Section 3.1. Starting in Section 3.2, the three categories of methods are described in detail. In Section 3.5, the applicability of the reviewed quantification methods is summarized and discussed.

3.1 Overview

3.1.1 Overall Framework and Challenges

Different from vehicle technology advances that can directly reduce traffic emission rates and contribute to air quality improvements, TFI strategies typically improve air quality through affecting travel demand and traffic flow. The most important step in quantifying TFI air quality impacts is to accurately measure their mobility impacts (e.g., speed, throughput, number of stops) at different times and geographical scales. The changes in mobility measures will affect traffic emission rates, which can be estimated relatively easily and accurately using tools such as MOtor Vehicle Emission Simulator (MOVES) [*75*]. Given the mobility measures and estimated traffic emission rates, the total emission impacts can then be calculated.

The following Figure 3.1 [*76*] provides a high-level summary of how the air quality impacts of TFI strategies can be quantified. Note that there exists an interactive relationship among Steps 1, 2, and 3 in Figure 3.1, which can be interpreted from the following main aspects:

- After a TFI project is implemented, existing users of the system (e.g., an arterial) will benefit directly and immediately from the project. This may attract travelers currently using other alternative corridors, generating induced traffic. Most likely, the induced traffic will be generated gradually, not overnight. Also, some users switching from other corridors may eventually switch back, as the mobility performance of the subject corridor may gradually deteriorate and the congestion levels of other corridors may improve due to the demand shift. Eventually, an equilibrium state will be achieved, meaning no travelers can switch to/away from the subject corridor to further improve her/his benefits.
- A TFI project may also generate induced demand due to mode shift, schedule shift, or new trips as a result of improved traffic. Similarly, the above

equilibrium concept can be applied to explain the short-term interactions between induced demand (Step 2 in Figure 3.1) and traffic operational improvements (Step 1 in Figure 3.1). Note that this report distinguishes induced traffic (attracted from other routes) from induced demand due to mode shift, schedule shift, and newly generated trips. The former is called induced traffic, while the latter ones are referred to as induced demand.

- Long-term air quality impacts are much more difficult to estimate. Other than the relocations of homes and businesses mentioned in Figure 3.1, many other factors can come into play, including energy policy that affects fuel prices, new vehicle powertrain technologies, connected and autonomous vehicles, and new developments in shared passenger and freight mobility.

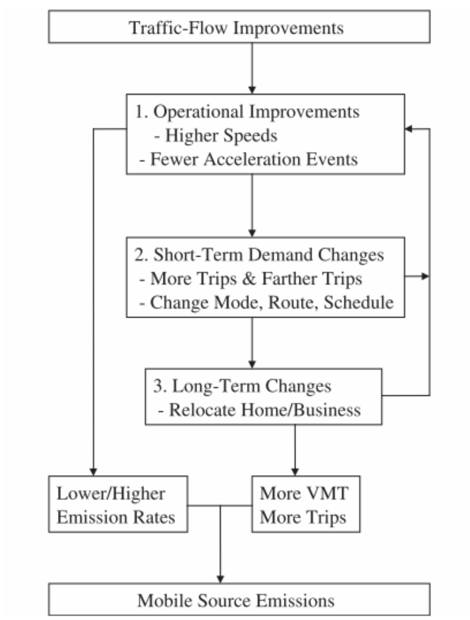

Figure 3.1: TFI Impacts on Mobility and Emissions

As noted in [*76*], Although it is desirable to account for both the short-term and long-term mobility impacts, in practice the long-term impacts are rarely considered explicitly. It may sound technically reasonable to estimate them through the well-known 4-step model or activity-based models. However, these models are typically for long-range transportation planning. They are intended for predicting the impacts of major changes to transportation system supplies, population, employment, land use, transportation and energy policies, etc. For small-scale TFI projects such as intersection signal re-timing, it is difficult for these long-range planning models to accurately estimate their traffic operational improvements. Substantial time and effort would have to be invested in collecting data (e.g., existing signal timing plans) and calibrating these models first. That said, for long-range planning projects, the model calibration work does not need to be performed at such a detailed level and usually there is no need to collect existing traffic signal timing data.

3.1.2 Overview of Mobility Impacts Estimation

Without relying on 4-step and activity-based travel demand models, various mobility performance changes due to TFI projects can be estimated based on the following methods [*76*]:

- ***Field Data Collection***: This method is often used in before-and-after studies to evaluate CMAQ TFI projects. For example, to evaluate the impacts of an arterial traffic signal re-timing project, a survey may be conducted to collect traffic volume, delay, and number of stops data [*77*] before and after the project is implemented. If the post-implementation data collection is conducted at an appropriate time, the short-term impacts of the project is likely to be captured implicitly. However, it is difficult to use this method for capturing a project's long-term impacts, as many influencing factors may change over time and differentiating their individual contributions is almost impossible. Also, using this method to measure impacts on neighboring corridors is challenging, as identifying the affected area and determining the best data collection points is not an easy task.
- ***Experience from Other Studies***: Collecting field data can be expensive. An alternative way of estimating project mobility impacts is based on experience from other studies. For a traffic signal coordination project in Tennessee [*78*], data from a toolbox developed by the Institute of Transportation Engineers (ITE) [*79*] was utilized to estimate the potential speed increase to be 3 mph. However, borrowing experience from other areas directly can be risky due to differences in site-specific factors. It would be even risker to use this method to evaluate long-term impacts and impacts on neighboring areas.
- ***Elasticity Analysis***: The elasticity of demand (denoted by A) with respect to an impact factor B is defined as the percentage change in A due to one percentage change in B. For example, the demand for HOV lanes (i.e., A) can be estimated through multiplying an elasticity by travel time saving (i.e., B). The idea behind the elasticity method is similar to borrowing experience from other studies, as elasticities are often derived from observed data or coefficients of statistical models. If the changes in B are outside the range of the observed data (or the input data to the statistical models), cautions should be exercised when applying the derived elasticities.
- ***Statistical Models***: Discrete choice models such as Multinomial Logit Model (MNL) and Nested Logit (NL) models are commonly used in modeling travel behavior (e.g., mode choice, departure time choice) given the attributes of various travel options. These attributes usually include travel time and costs and are collected via surveys. The MNL and NL models can be implemented in a "pivot-point" or "incremental" manner, so that only the baseline/initial shares of different choices and changes in key attributes are needed to predict the new shares of those choices (see the example [*80*] below).

$$P_i' = \frac{P_i \times \exp(\Delta u_i)}{\sum_{j=1}^{k} P_j \times \exp(\Delta u_j)}$$

P_i = baseline/initial probability of choosing mode i;
P_i' = new probability of choosing mode i;
Δu_i = changes in utility value for mode i;
k = number of available travel mode choices;
j = index of travel mode choices;

3.1.3 Overview of Emission Impacts Estimation

As shown in Figure 3.1, translating mobility changes into emission benefits mainly takes into consideration: (1) VMT, (2) number of trips, and (3) emission rates. The first two factors can be estimated based on the mobility analysis results. While for emission rates, they depend on vehicle speed as well as vehicle composition, fuel type, meteorology, etc.

For major TFI projects that generate significant mobility impacts, the speed changes can be estimated using regional travel demand and traffic assignment models. A simplified approach is to directly estimate the speed changes at the project level based on the relationship among speed, traffic volume, and capacity. In some sketch planning methods, elasticity analysis is adopted to estimate speed with respect to VMT changes.

The speed data together with local parameters (e.g., vehicle composition) are fed into emission models such as MOVES and EMFAC [*81*] to obtain emission rates for different vehicle speeds, which are then combined with VMT and number of trips information to calculate total emissions.

It is important to note that the above approach cannot adequately consider emissions due to acceleration/deceleration and idling [*76*], which are important for traffic signal timing related TFI projects. To address this issue, traffic simulation can be used to generate vehicle speed profiles for more detailed emission analysis.

3.1.4 Cost-Effectiveness Analysis (CEA)

Cost-Effective Analysis (CEA) is an important step in the TFI project benefits quantification process. Its results are important for ranking various TFI strategies and are often desired by decision makers. However, the TFI project CEA results usually are site-specific. Local factors such as existing congestion level can significantly affect the cost-effectiveness of a project. Nevertheless, given enough project samples, the CEA results may still be useful in providing a rough range for the cost-effectiveness of a TFI strategy.

Each TFI project is usually associated with multiple performance measures such CO, VOC, and fuel and travel time saving. To perform CEA and facilitate strategy comparison, it is necessary to assign proper weights to each measure. For example, a study by the National Research Council proposed a uniform approach [*82*] to weigh pollutants and derived a single cost-effectiveness estimate. Depending on how the weights are selected, the CEA result of a TFI project may also vary.

For TFI project CEA, the project costs (e.g., capital and operating) are usually annualized over the life of the project and compared to the estimated annual emission and mobility benefits. The benefits for each year over the project life are typically assumed to be the same, while the benefits for years beyond the project life is not considered. In reality, the project benefits most likely will change over years. However, these changes are rarely modeled. One challenge to modeling the long-term project benefits variations probably is the changes in emission rates, which are affected by many uncertain factors such as vehicle technology and energy policy. Although Burmich [*83*] proposed a set of emission rates (see Figure 3.2) for long-term TFI project emission benefits analysis, these rates have not been officially endorsed by any agencies such as the EPA. Given that alternative fuel vehicles are getting increasing attention, it is questionable whether these rates are still applicable.

(Fleet of Light-Duty Passenger Vehicles, Light-Duty Trucks and Motor Cycles)

Analysis Period or Project Life	1-5 Years (2008-2012)	6-10 Years (2008-2017)	11-15 Years (2008-2022)	16-20 Years (2008-2027)
ROG				
VMT (g/mile)	0.277	0.231	0.200	0.180
commute trip ends (g/trip end)	1.023	0.860	0.738	0.646
average trip ends (g/trip end)	0.762	0.644	0.555	0.488
NOx				
VMT (g/mile)	0.324	0.263	0.220	0.189
commute trip ends (g/trip end)	0.462	0.380	0.315	0.267
average trip ends (g/trip end)	0.444	0.368	0.307	0.260
PM2.5				
VMT (g/mile)	0.050	0.050	0.051	0.051
running exhaust only (g/mile)	0.015	0.015	0.016	0.016
tire and brake wear (g/mile)	0.007	0.007	0.007	0.007
road dust (g/mile)	0.028	0.028	0.028	0.028
commute trip ends (g/trip end)	0.015	0.015	0.016	0.016
average trip ends (g/trip end)	0.008	0.008	0.008	0.008
CO				
VMT (g/mile)	3.365	2.758	2.338	2.044
commute trip ends (g/trip end)	8.784	7.381	6.274	5.427
average trip ends (g/trip end)	6.289	5.270	4.472	3.862

Figure 3.2: Average Auto Emission Factors

3.2 Sketch Planning Methods

Compared to full-scale travel demand models, sketch planning methods are much easier to use and are more popular for quantifying the benefits of TFI projects. The following sketch planning methods have been identified and reviewed in this study, and they are further described in the rest of this subsection, which is drawn heavily from a report [*76*] prepared for the FHWA.

- TCM analyst
- CM/AQ evaluation model
- TCM tools
- Off-Network tool set
- California standardized method
- RAQC workbook
- MWCOG sketch-planning methods
- NCTCOG sketch-planning methods
- Quick-HOV
- ITS Deployment Analysis System (IDAS)
- FIXiT 2.0
- CMAQ emissions calculator toolkit
- ME-CMAQ
- Automated-CE
- CMAQ analysis methods
- Ohio CMAQ toolbox

3.2.1 Detailed Review of Individual Sketch Planning Methods

3.2.1.1 TCM analyst

Overview: The Transportation Control Measures (TCM) analyst [*84,85*] is a spreadsheet emission analysis tool based on methodologies developed for the U.S. EPA. It can be used to analyze the traffic emission benefits of the following strategies:

- Improved transit
- ***HOV lanes***
- Carpooling and vanpooling promotion
- Telecommute and work hour strategies
- ***Traffic flow improvements***

Methodology: This tool utilizes elasticity analysis to estimate travel demand based on cost and time, and speed derived from VMT. Factors such as trip lengths and previous travel modes are considered in the elasticity analysis. Emission factors for processes such as hot start, cold start, and running are estimated using MOBILE and applied to the mobility analysis results to predict emission impacts.

Input Data: Depending on the strategy being analyzed, the data needed may vary. For the strategies listed above, the following data elements are needed: travel data (e.g., person and vehicle-trips, trip length, peak and off-peak speeds, average carpool size); census data (e.g., number of workers, persons per household, vehicle ownership); potential number of users; and MOBILE emission factors by speed, type, and operating mode. For some strategies, assumptions for elasticities and participation rates are also needed.
Outputs: Changes in trips, VMT, average travel speeds, and emissions.
Advantages: This tool implements EPA emission models and considers the emission impacts of many factors, including vehicle type, work versus non-work trips, peak versus off-peak travel, induced demand, and changes in trip lengths.
Limitations: this tool requires an extensive set of baseline regional travel data and emission factors. Also, assumptions regarding elasticities, induced demand, and participation rates need to be made, and this can be subjective and challenging. The tool was initially developed in 1994 and seem that it has not been frequently updated and maintained since then. The spreadsheets are not available online.

3.2.1.2 CM/AQ evaluation model

Overview: The Congestion Mitigation/Air Quality (CM/AQ) evaluation model is a program developed based on the Paradox database software. It can model the emission benefits of a wide variety of CMAQ (a total of 59) strategies, including:

- Improved transit
- ***HOV lanes***
- Park and ride
- Carpooling and vanpooling promotion
- Bicycle and pedestrian facilities
- ***Traveler information***
- Telecommuting/work hours
- Pricing/subsidies
- Parking management
- ***Traffic flow improvements***
- Intermodal freight
- Traffic calming
- Idle control
- Cold start
- Alternative fuel vehicles

Methodology: Originally developed by JHK Associates for the Denver Regional Council of Governments, this model was later adapted by the Texas Transportation Institute for use in Texas [*86*]. The methodologies used in this tool are similar to those in the TCM tools below. Travel demand changes are estimated using elasticities, while users have to make assumptions about program participation. This tool estimates emissions based on changes in VMT, trips, speed and user-entered emission factors. It can also analyze the cost-effectiveness of strategies and rank them.

Input Data: Users need to provide baseline travel characteristics (e.g., number of person-trips, percent of trips in peak period), behavioral assumptions (elasticities or participation), and local emission factors from the MOBILE and PART5 models, although default values are provided in many cases.
Outputs: Changes in trips, VMT, speed, idling time for peak and off-peak periods, and emissions.
Advantages: It covers many CMAQ strategies and is easy to use. Based on user-supplied weights, it can also perform cost-effectiveness analysis and rank strategies, which is not available in many other tools reviewed in this research. It takes into consideration idling, cold-start, hot-start, and reduced VMT.
Limitations: It requires users to be familiar with Paradox and provide many local data such as emission factors, baseline travel characteristics, program participation rates (e.g., telecommuting participants, number of new walkers/bicyclists), and assumptions regarding elasticities.

3.2.1.3 TCM tools

Overview: TCM Tools were developed by Sierra Research and JHK Associates. They have been applied in major cities such as San Diego, Houston, and Tucson. They can be used for CMAQ strategies including [*76*]:

- Improved transit
- ***HOV lanes***
- Park and ride
- Carpooling and vanpooling promotion
- Employer-based travel demand management
- Bicycle and pedestrian facilities
- Telecommuting/work hours
- Pricing/subsidies
- Land use

Methodology: The Excel-based TCM tools estimate area-wide changes in peak and off-peak vehicle trips, VMT, and vehicle speeds based on elasticities and assumptions of program participation. The emissions module is written in Fortran and it estimates emissions based on MOBILE and EMFAC factors considering changes in VMT, trips, and speed.
Input Data: The mobility module requires the same data as for the CM/AQ evaluation model. The emissions module requires VMT, speeds by six facility types, vehicle registration distribution, ambient temperature, etc.
Outputs: Changes in mode share, vehicle-trips, VMT, average travel speed, and emissions.
Advantages: They cover many CMAQ strategies.
Limitations: For many strategies, TCM tool require the user to estimate the participation rates and elasticities, which directly affect the magnitude of the estimated travel impacts. The TCM tools are not user friendly in terms of managing scenarios.

3.2.1.4 Off-Network (Off-Net) tool set

Overview: The Off-Network (Off-Net) tool set is very similar to PAQONE. Off-Net was initially developed for the Pennsylvania DOT (PennDOT) by COMSIS Corporation, and was later modified by Cambridge Systematics, Inc., Michael Baker Associates, and E.H. Pechan for the Illinois DOT. Off-Net is a Windows-based software package. PAQONE was developed by Michael Baker Associates for PennDOT. Compared to Off-Net, PAQONE is able to model additional employer-based and region wide TDM strategies [*76*]. Off-Net can analyze:

- Improved transit
- Park and ride
- Employer-based TDM
- Bicycle and pedestrian facilities
- ***Traveler information***
- ***Traffic flow improvements***
- ***Incident management.***

Methodology: Off-Net is based on sketch-planning analysis, elasticities, and highway/traffic engineering principles from the Highway Capacity Manual. Its mobility module considers vehicle-trips by time of day and work versus non-work trips; and VMT changes by time of day, facility type, and area type. It includes a stand-alone emissions module that estimates emission factors using MOBILE.
Input Data: The data needs vary across strategies being analyzed, including existing transit ridership, population of transit or bicycle route service areas, baseline speeds and volumes, and changes in transit, bicycle, or roadway service characteristics.
Outputs: Vehicle-trips, VMT, and emissions.
Level of Effort: The models are Windows-based applications that are easy to use. The software includes a scenario management function. Some effort is required to develop baseline data and assumptions.
Advantages: The windows-based tool includes a scenario management component and is relatively easy to use. The use of VMT and speed data by facility type generate output that is consistent with the emissions estimates based on travel demand models.
Limitations: Some assumptions need to be made regarding the model input data.

3.2.1.5 California standardized method

Overview: It is a spreadsheet-based tool that converts number of participants in a TDM program into travel changes, emissions benefits, and cost-effectiveness [*87*]. It has been applied by the California Air Resources Board (CARB) and the Los Angeles Metropolitan Transportation Authority (LAMTA). The underlying method is generic and makes this tool applicable to other states. This tool can be used for analyzing:

- Improved transit
- Carpooling and vanpooling promotion
- Employer-based TDM

- Telecommuting/work hours
- Pricing/subsidies

Methodology: The tool requires users to provide either post- and/or pre-implementation survey data, or mode shift forecasts to estimate emissions benefits.
Input Data: It requires the numbers of participants before and after the implementation of a TDM program, average trip length, emission factors (per trip and per mile).
Outputs: Changes in vehicle-trips, VMT, and emissions.
Advantages: It accounts for prior mode of travel, trip lengths, changes in transit service, and changes in personal vehicle travel in calculating emissions reductions. The method and tool are straightforward and easy to apply.
Limitations: Similar to other tools/methods, this California standardized method requires uses to provide estimates of program participation. It relies on users to provide program participation rates (e.g., through surveys) and emission factors.

3.2.1.6 RAQC workbook

Overview: The workbook was developed for the Regional Air Quality Council (RAQC) in Denver, Colorado. It covers the following strategies [*76*]:

- Improved transit
- ***HOV lanes***
- Carpooling and vanpooling promotion
- Employer-based TDM
- Bicycle and pedestrian programs
- Telecommute and work hour strategies
- Pricing and subsidies
- Land use

Methodology: This workbook estimates trip and/or VMT impacts using elasticities and data from the literature. Emissions are calculated based on estimated VMT.
Input Data: It requires data such as total employees, persons, and vehicles affected; baseline vehicle trips per employee; and total regional VMT. It provides default parameters such as average trip lengths and emission factors that can be replaced by local data.
Outputs: Changes in VMT and emissions.
Advantages: The workbook and the underlying method are straightforward and easy to understand.
Limitations: The workbook is in paper format and not automated. Determining appropriate elasticities and empirical factors takes time and is challenging. The analysis results depend heavily on the accuracy of baseline parameters such as vehicle operating cost per mile.

3.2.1.7 MWCOG methods

Overview: These sketch planning methods were developed by the Metropolitan Washington Council of Governments (MWCOG) for analyzing the emissions benefits of TCM strategies. They are often used in conjunction with MWCOG's TDM Evaluation Model and regional mode choice model, and can analyze more than 50 strategies, including [*76*]:

- Park and ride
- Carpooling and vanpooling promotion
- Bicycle and pedestrian facilities
- ***Traveler information***
- Telecommuting/work hours
- Pricing/subsidies
- Land use
- Idle control

Methodology: These methods are meant for regional-level strategies based on many assumptions such as program effectiveness, prior mode of travel, and trip lengths. The methods analyze work and non-work trips separately. The emissions analysis accounts for cold start, hot start, and running (e.g., VMT) factors.
Input Data: These methods require data such as total number of park-and-ride spaces, average trip lengths, program participation rates, employment affected, and existing mode shares.
Outputs: Changes in vehicle-trips, VMT, and emissions.
Advantages: Sample calculations are provided for some strategy types and methods are clearly documented.
Limitations: Due to the lack of data and analytical procedures, some input parameters are determined arbitrarily based on local experience. Such assumptions and calculation approaches may not be applicable to other places.

3.2.1.8 NCTCOG sketch-planning methods

Overview: The methods developed for the North Central Texas Council of Governments (NCTCOG) can analyze strategies such as

- Improved public transit
- ***HOV facilities***
- Employer-based TDM
- Trip reduction ordinances
- ***Traffic flow improvements***
- Park and ride/fringe parking
- Vehicle use limitations and restrictions
- Area-wide rideshare incentives
- Bicycle and pedestrian programs
- Extended vehicle idling

- Extreme low temperature cold starts
- Work schedule changes
- Activity centers
- Accelerated vehicle retirement
- Parking management
- Vehicle purchases and repowering
- Congestion pricing

Methodology: The methods are detailed in a report titled "The Texas Guide to Accepted Mobile Source Emission Reduction Strategies" [*88*].
Input Data: The NCTCOG methods use a wide range of data including demographics, travel demand model outputs, VMT and speed by vehicle class, vehicle age distribution, ambient temperature, and professional judgment.
Outputs: Changes in emissions.
Advantages: The methods are well documented and a set of spreadsheet tools are available to facilitate the calculations. Emissions factors can be generated using MOBILE, MOBILE6, or MOVES.
Limitations: The methods require users to provide travel demand and traffic flow impact results estimated based on either experience or collected data.

3.2.1.9 Quick-HOV

Overview: Quick-HOV is developed specifically for modeling the impacts of HOV lanes on vehicle occupancy, congestion, air quality, fuel consumption, etc.
Methodology: It uses demand characteristics and the travel times of different facilities to predict demand shifts. Emission factors are generated using MOBILE5 or EMFAC based on speeds and traffic composition to estimate total emissions.
Input Data: It requires the characteristics (e.g., capacity, length) of the HOV facility and other parallel roads. Other required data includes peak-period and free-flow travel times, vehicle volumes, and person volumes.
Outputs: Changes in person travel, vehicle travel, auto occupancy, congestion, delay, air quality, and fuel consumption.
Advantages: It is a Windows program and is relatively easy to use. The underlying methods are straightforward and the calculation steps are clearly documented. It is considered more accurate than sketch-planning approaches included in other TCM tools.
Limitations: It does not consider network-level changes in travel patterns or traffic flow characteristics.

3.2.1.10 ITS Deployment Analysis System (IDAS)

Overview: The IDAS tool can quantify the benefits and costs of more than 60 ITS strategies (either combined or individual). It can analyze strategies such as

- Improved transit
- ***HOV lanes***
- ***Traveler information***

- ***Traffic flow improvements***
- ***Incident management***

Methodology: This tool can analyze CMAQ strategies at both network and traffic analysis zone levels. For some strategies, the “pivot-point” approach is utilized to estimate mode choice, temporal choice, and induced/foregone demand based on coefficients from regional travel demand models. For other strategies, data from empirical studies are utilized to estimate their impacts. Emission factors are estimated using MOBILE5 or EMFAC.
Input Data: Transportation network and trip tables by mode and/or purpose from the regional travel model; and locations and types of ITS strategies to be analyzed.
Outputs: Changes in vehicle-trips, VMT, emissions; travel time savings and improvements in travel time reliability; energy consumption, noise impacts, safety impacts, and monetary values of these changes; and lists of ITS equipment and costs.
Advantages: It can analyze many ITS strategies. Network-wide VMT and speeds are used to estimate emissions. Also, it is able to consider time-of-day shifts, induced demand, and changes in travel time reliability. The software is user friendly.
Limitations: Users need to be familiar with travel demand models, and running the model may take up to a few hours depending on the size of the network.

3.2.1.11 FIXiT 2.0

Overview: FIXiT (Future Improvement Examination Technique) is a sketch planning tool developed by the Texas A&M Transportation Institute [*89*] for analyzing congestion mitigation and mobility strategies. It can model 41 congestion mitigation strategies for road segments and 77 strategies for urban area improvement.
Methodology: FIXiT 2.0 first determines the delay reduction effect of a strategy and multiplies that by the existing delay of a facility. This approach is very straightforward and enables multiple strategies to be analyzed simultaneously and compared easily.
Input Data: Applying this tool requires (1) a master table of delay reduction benefits for each congestion mitigation strategy based on observed information; and (2) measured existing delay for the transportation facility to be analyzed.
Outputs: Different types of delay by time of day with low/high scenario for each strategy.
Advantages: The straightforward idea behind FIXiT dramatically simplifies the mobility analysis process, making it easy to analyze and compare multiple strategies simultaneously at five different impact levels (spot, corridor, local, regional, and state). This tool can also take observed data from before-and-after studies to analyze congestion mitigation strategies.
Limitations: The reliability of the master table (see *Input Data*) directly determines the accuracy of the final analysis results. Developing this master table can be time-consuming, particularly if done through local before-and-after studies. On the other hand, users should be cautious about data generalizability when the findings from none-local before-and-after studies are utilized to derive the master table. Also, applying FIXiT requires users to collect existing delay data for the facility to be analyzed.

3.2.1.12 CMAQ emissions calculator toolkit

Overview: The CMAQ Emissions Calculator Toolkit was developed by the FHWA Office of Natural Environment [*90*]. It consists of a set of spreadsheet-based tools for estimating the air quality benefits of CMAQ strategies, including:

- Transit bus and fleet expansion
- Transit bus retrofits and replacement
- Carpooling and vanpooling
- Alternative fuels and vehicles
- Advanced diesel truck/engine technologies
- ***Congestion reduction and traffic flow improvements (intersection improvements, traffic signal synchronization, and roundabouts)***

Methodology: The emission calculations using this toolkit rely on the "idling" and "running" emission rates generated by MOVES. The running emission rates are mainly used for the *Traffic Signal Synchronization* tool and the idling emission rates are for the *Intersection Improvements* and *Roundabouts* tools. The emission rates are obtained through multiple project-level MOVES runs. Before a project-level run can be done, it is often necessary to first complete a national-scale MOVES run to generate fleet mixes, fuel mixes, and activity rates that are needed for project-level runs.
Input Data: Information required for a national-scale run in MOVES; information needed for a project-scale run in MOVES such as AADT, truck percentage, observed or estimated existing delay; and information related to the proposed strategy such as timing plan.
Outputs: Performance improvements such as delay reduction and total emissions for five pollutants – CO, PM2.5, PM10, NOx, and VOC – in kilograms/day.
Advantages: It is developed and recommended by the FHWA. The spreadsheet-based tools are easy to use and the underlying methods are well documented. The input information generated by the initial national-scale run helps to produce more reliable emission estimates.
Limitations: The toolkit covers a very limited number of CMAQ TFI strategies.

3.2.1.13 ME-CMAQ

Overview: The ME-CMAQ (Methodologies for Evaluating Congestion Mitigation and Air Quality improvement projects) was developed by the Maricopa Association of Governments [*91*]. It covers the following strategies:

- Bicycle and pedestrian facilities
- Bus and light rail projects
- Diesel retrofits and anti-idling programs
- ***Intersection improvements (additional turning lanes, and roundabout)***
- Natural gas and electric vehicles
- Park and ride facilities
- ***Paving projects***

- Rideshare programs
- ***Traffic flow improvements (traffic signal coordination, and Intelligent Transportation Systems)***
- Trip reduction program

Methodology: This tool estimates the traffic operation improvements (e.g., delay reduction rate, speed increase rate) from a reference table derived based on previous studies. These improvements are combined with emission factors from MOVES to estimate daily emission reductions. In the final stage of calculating cost-effectiveness, capital recovery factor that incorporates project lifespan is considered.
Input Data: CMAQ project cost; pre-project conditions such as ADT, speed, delay, etc.
Outputs: Daily emission reductions, project cost-effectiveness.
Advantages: The methodologies are clearly documented and straightforward. They are implemented as Excel spreadsheets and are easy to apply.
Limitations: The estimates of operational benefits may not be accurate since the performance improvement factors are obtained directly from other studies. Local before-and-after studies or computer simulations could be adopted to address this deficiency.

3.2.1.14 Automated-CE

Overview: The Automated Methods to Find the Cost-Effectiveness of Funding Air Quality Projects (Automated-CE) [*83*] was developed by the California Air Resource Board (CARB). They can be used to analyze:

- Cleaner off-road vehicles
- ***Signal coordination***
- Cleaner on-road vehicles
- Bicycle facilities
- New bus service
- Telecommuting programs
- Vanpools and shuttles
- Ridesharing and pedestrian facilities
- Cleaner street sweepers

Methodology: Automated-CE is very similar to ME-CMAQ.
Input Data: Automated-CE requires similar input data as ME-CMAQ does.
Outputs: Annual emission reduction, project cost-effectiveness.
Advantages: Database-based tools have been developed for agencies to evaluate CMAQ strategies in a straight-forward way.
Limitations: It only covers one CMAQ TFI strategy (i.e., signal coordination).

3.2.1.15 CMAQ analysis methods

Overview: CMAQ Analysis Methods were developed by Cambridge Systematics for MassDOT. The strategies covered by these methods include:

- Alternative fuels
- ***Traffic flow improvements (intersection signalization, intersection coordination, geometry improvements)***
- Anti-idling strategies
- Bicycle and pedestrian facility
- Bike sharing
- Bus replacement
- Complete streets
- New bus or shuttle service
- Park and ride lot
- Speed reduction
- ***Transit signal priority***
- Truck stop electrification

Methodology: Elasticity analyses are utilized to account for the impacts of induced demand. The cost-effectiveness of the first build year is calculated for the purpose of comparison among candidate strategies.
Input Data: Traffic data, observed delay, etc.
Outputs: Annual emission reductions, and project cost-effectiveness.
Advantages: Straightforward elasticity regression models are developed to account for the impacts from induced demand. Excel spreadsheet-based tools are easy to apply.
Limitations: Similar to many other tools, the methods only consider the cost-effectiveness of CMAQ projects in first year after build. In other words, long-term impacts are not taken into consideration.

3.2.1.16 Ohio CMAQ toolbox

Overview: The Ohio CMAQ toolbox was developed by the Mid-Ohio Regional Planning Commission. The strategies covered by this toolbox include:

- **Arterial project**
  - **Delay-based method**
  - **Speed-based method**
- **Intersection or roundabout improvements**
- **Signal coordination**
- Fleet vehicles
- Transit server expansion
- Park and ride
- Multi-use path or trail
- Grade separation
- Freight rail yard

Methodology: HCM methods or simulation tools like Synchro are required to estimate delay and average speed for the build year.
Input Data: Traffic volume data, observed delay, estimated delay, etc.

Outputs: Daily emission reductions for various pollutants.
Advantages: Both idling emissions and speed-based emissions are considered. The toolbox is in the form of an Excel spreadsheet and is easy to use.
Limitations: This toolbox cannot generate cost-effectiveness measures. Also, delay analysis is not included in the toolbox and additional delay analyses or tools are needed.

Table 3.1 Comparison of Sketch Planning Methods

Methods	Ease of use*	Method for changes in trip and/or induced demand	Level of detail/factors considered	TFI strategies addressed	Availability/being properly maintained?
TCM analyst	●●○○○	Elasticity analysis	vehicle type, work vs. non-work trips, peak vs. off-peak travel, induced demand, and trip length changes	HOV lanes, traffic signalization, intersection improvement	no tools online, but manual exists1
CM/AQ evaluation model	●●●●○	Elasticity analysis	peak vs. off-peak travel, induced demand	HOV lanes, TIS, and some other TFI strategies	no tools online, but manual exists[1]
TCM tools	●●●●○	Elasticity analysis	peak vs. off-peak travel, induced demand	HOV lanes	No detailed information online
Off-Net tool set	●●●●○	None	Work vs. non-work trips, time of day	TIS, incident management systems, some other TFI strategies	No detailed information online
California standardized method	●●●●○	None	Mode of travel, trip length	None	No tools online, but report available[1]
RAQC methods	●●●○○	Elasticity analysis	Mode of travel, trip length	HOV lanes	No detailed information online
MWCOG methods	●●●○○	None	Mode of travel, trip length	TIS	No detailed information online
NCTCOG methods	●●●○○	None	Travel demand, vehicle class, vehicle age distribution, ambient temperature	HOV lanes, some other TFI strategies	No tools found, report available[2]
Quick-HOV	●●○○○	Yes, demand shifts are predicted by demand characteristics and the travel times of different facilities.	Demand shift, peak-period and free-flow travel times	HOV lanes	Cannot find tools online

Methods	Ease of use*	Method for changes in trip and/or induced demand	Level of detail/factors considered	TFI strategies addressed	Availability/being properly maintained?
IDAS	●○○○○	Yes, rigorous travel demand model is used.	time-of-day shifts, induced demand, and changes in travel time reliability	HOV lanes, TIS, incident management, some other TFI strategies	Need to purchase
FIXiT 2.0	●●●●●	Travel demand changes are reflected implicitly in the master table (before-after studies)	delay by time of day, various demand scenario	41 strategies for segments improvement, and 77 for urban area congestion relief.	No tools online, but report exists[2]
CMAQ Emissions Calculator Toolkit	●●●●○	None	national fleet mixes, fuel mixes, and activity rates	Intersection improvements, traffic signal synchronization, and roundabout	Tools available[3]
ME-CMAQ	●●●●○	None	capital recovery factor, project lifespan	Additional turning lanes, roundabout, paving projects, traffic signal coordination, and ITS	Report available[2]
Automated-CE	●●●●○	None	capital recovery factor, project lifespan	Signal coordination	Tools available[3]
CMAQ Analysis Methods	●●●●○	Elasticity analysis	First build year cost-effectiveness	Intersection signalization, Intersection coordination, Channelization, ITS	Tools available[3]
Ohio CMAQ toolbox	●●●●○	None	peak vs. off-peak travel, idle emissions and moving emissions	Intersection signalization, roundabout, intersection coordination, and all other arterial projects.	Tools available[3]

* more black circles mean the corresponding method is easier to use.

[1] paper exists but unable to download.

[2] report exists and downloaded into reference folder.

[3] tools were downloaded into reference folder, as well as documentation if there is one.

Table 3.2 Inputs and Outputs of Sketch Planning Methods

TFI strategies	Evaluation method	Key input	Output
Adding/ Upgrading Traffic Signal and Related Hardware and Software	CMAQ emissions calculator toolkit	Existing delay, traffic volumes, intersection geometry, and proposed conditions (e.g. timing plan)	Delay reduction, emissions
	CMAQ Analysis methods	Existing delay and delay after improvements, and corresponding traffic volumes	Emissions, first year cost-effectiveness
Traffic retiming/ synchronization	TCM analyst	Percent change in traffic speed, and affected VMT	Emissions
	CM/AQ evaluation model	Percent change in traffic speed, and affected VMT	Emissions
	Off-Net tool set	Percent change in traffic speed, and affected VMT	Emissions
	NCTCOG methods	Project-specific average speed improvements, and traffic volumes	Emissions
	FIXiT 2.0	Existing delay, and selecting depression values in master table	Delay reduction in different forms
	CMAQ emissions calculator toolkit	Corridor length (synchronization), existing corridor travel time, etc.	Peak- and off-pick-hour travel time savings, emissions
	ME-CMAQ	CMAQ Cost, length of project, current traffic, pre-project speed, and the category of proposed project	Increase in speed, emissions, cost-effectiveness
	Automated-CE	Funding dollars, peak-hour traffic volume, length of roadway, before and after average traffic speeds.	Emissions, cost-effectiveness
	CMAQ Analysis methods	Existing delay and delay after improvements, and corresponding traffic volumes	Emissions, first year cost-effectiveness
	Ohio CMAQ toolbox	Intersection ADT and existing and future delay for peak and off-peak period,	Daily emission reduction

TFI strategies	Evaluation method	Key input	Output
Transit Signal Priority	CMAQ Analysis methods	Project details such as number of lanes, and peak hour volume. Traffic signal information, e.g. cycle length. And transit information such as transit headways, and transit ridership etc.	Delay/VMT impact, Emissions, first year cost-effectiveness
Roundabout	TCM analyst	Percent change in traffic speed, and affected VMT	Emissions
	CM/AQ evaluation model	Percent change in traffic speed, and affected VMT	Emissions
	Off-Net tool set	Percent change in traffic speed, and affected VMT	Emissions
	NCTCOG methods	Project-specific average speed improvements, and traffic volumes	Emissions
	FIXiT 2.0	Existing delay, and selecting depression values in master table	Delay reduction in different forms
	CMAQ emissions calculator toolkit	Existing intersection type, traffic volumes, delay, and proposed conditions, e.g. number of circulating roundabout lanes	Delay reduction, emissions
	ME-CMAQ	CMAQ cost, and total weekday vehicle hours of delay reduced	Emissions, cost-effectiveness
	Ohio CMAQ toolbox	Intersection ADT and existing and future delay for peak and off-peak period,	Daily emission reduction
Other intersection improvements	TCM analyst	Percent change in traffic speed, and affected VMT	
	NCTCOG methods	Project-specific average speed improvements, and traffic volumes	Emissions
	FIXiT 2.0	Existing delay, and selecting depression values in master table	Delay reduction in different forms
	ME-CMAQ	CMAQ cost, and total weekday vehicle hours of delay reduced	Emissions, cost-effectiveness

TFI strategies	Evaluation method	Key input	Output
	CMAQ analysis methods	Existing delay and delay after improvements, and corresponding traffic volumes	Emissions, first year cost-effectiveness
Managed lanes	TCM analyst	Number of HOV lane-miles	Trips, VMT
	CA/AQ evaluation model	Increase in number of HOVs	Trips, VMT, emissions
	TCM tools	Miles of HOV lanes added	Trips, VMT, emissions
	RAQC workbook	-	VMT, emissions
	NCTCOG sketch-planning methods	Before/after traffic volumes and speed; length of facilities	Emissions
	Quick-HOV	Traffic volumes and physical characteristics of HOV lanes and parallel facility	Trips, emissions
	IDAS		
	FIXiT 2.0	Existing delay, and selecting depression values in master table	Delay reduction in different forms
Highway/ Freeway Management	-	-	-
Highway Traveler Information Systems	CM/AQ evaluation model	Percent increase in transit	Emissions
	Off-net tool set	Freeway section length, baseline speed and volume	Emissions
	IDAS	Types and locations of deployed strategies	Emissions
	FIXiT 2.0	Existing delay, and selecting depression values in master table	Delay reduction in different forms
Shoulder Paving/ widening	FIXiT 2.0	Existing delay, and selecting depression values in master table	Delay reduction in different forms
Pavement Resurfacing/ Rehabilitation	FIXiT 2.0	Existing delay, and selecting depression values in master table	Delay reduction in different forms
	ME-CMAQ	CMAQ cost, project length, ADT, the number of access points to be paved etc.	Emissions, cost-effectiveness

TFI strategies	Evaluation method	Key input	Output
Turn Lanes and Median Construction	FIXiT 2.0	Existing delay, and selecting depression values in master table	Delay reduction in different forms
	ME-CMAQ	CMAQ cost, total weekday vehicle hours of delay reduced	Emissions, cost-effectiveness
Ramp Geometric Improvements	FIXiT 2.0	Existing delay, and selecting depression values in master table	Delay reduction in different forms
Road segment improvements	TCM analyst	Percent change in traffic speed, and affected VMT	Emissions
	Off-Net tool set	Percent change in traffic speed, and affected VMT	Emissions
	NCTCOG methods	Project-specific average speed improvements, and traffic volumes	Emissions
	FIXiT 2.0	Existing delay, and selecting depression values in master table	Delay reduction in different forms

3.2.2 Comparison of Different Methods

Table 3.1 compares the sketch planning tools in terms of ease of use (more black circles mean the corresponding method is easier to use), method used to model trip changes and induced demand, level of detail considered, TFI strategies addressed, and availability (whether the tools have been properly maintained and are up-to-date). Table 3.2 summarizes the sketch planning tools that can be used for each TFI strategy. The required input and output in each case are also provided in this Table.

3.3 Simulation Methods

Traffic simulation is another viable solution to model the mobility and emission impacts of TFI strategies. Simulation can be done at different levels (e.g., macroscopic, mesoscopic, and microscopic), which affects the accuracy of the simulation results. In general, microscopic simulations take a longer time (manageable even with regular desktop computers) but can generate more detailed results than macroscopic traffic simulations. Regardless of the simulation level (e.g., micro, macro), the accuracy of traffic simulation also depends significantly on how the model is created and calibrated.

Compared to sketch planning tools, simulation models offer the following benefits:

- They do not require users to make subjective assumptions (e.g., percent reduction in delay) that can substantially affect the mobility modeling results;
- Multiple simulation runs with different random seeds allow users to estimate the worst, mean, median, and best performances of a strategy. The robustness of a strategy can then be relatively easily evaluated, which is important for making informed decisions;
- Simulation makes it possible to compare the operations of a facility before and after the implementation of a TFI strategy under exactly the same traffic demand, while it is almost impossible to do so by conducting before-and-after studies; and
- Simulation tools can generate detailed vehicle speed profiles, which can be combined with emission rates generated by MOVES to obtain accurate emission estimates. Although many traffic simulation tools (e.g., Synchro) have built-in modules for estimating emissions, using the MOVES results takes local factors into account and is considered to be more accurate.

Using computer simulation for evaluating TFI strategies also has limitations:

- It usually requires a considerable amount of time to code the simulation network and, in some cases, to learn different simulation tools;
- Using simulation sometimes still requires users to make subjective assumptions. For example, VISSIM provides a module for modeling HOV and HOT lanes. However, users need to provide parameters for the discrete choice model in that module to estimate how travelers may shift from single-occupancy vehicles to carpooling; and
- Simulation studies typically require collecting a lot of input data and data for model calibration, which is challenging and costly. This issue is not unique for simulation studies. For the same project, a before-and-after study often needs to collect more data than a simulation study, as the simulation study only requires data before the project implementation.

A wide range of simulation tools such as VISSIM, Aimsun, SUMO (free), SimTraffic, TSIS/CORSIM, SIDRA, and Paramics can model most of the TFI strategies identified in this research, particularly traffic signal control, roundabout, managed lanes, ramp meters, etc. For some TFI strategies such as adding curbs and medians, channelization, pavement resurfacing, dynamic message signs, and time to destination display, their impacts on mobility and air quality depend on how drivers respond to these strategies. Although they can still be modeled by the previous microscopic simulation tools, users would need to make additional assumptions to be used as the simulation input. For instance, how many drivers will switch routes based on the dynamic message sign content and how the newly paved roadway may improve the average travel speed. Clearly, these assumptions will affect the simulation results. In addition to the microscopic simulation tools mentioned earlier, HCS, Rodel, Vistro, and PASSER, Synchro, and Transyt-7F have also been widely used for analyzing intersection control TFI strategies.

The above list of simulation and analytical tools is not meant to be exhaustive, since there are so many analysis tools. Also, each tool has its pros and cons. Listing these tools does not mean they are endorsed or recommended. Sometimes, it is better to use a tool that the analyst is most familiar with rather than a tool that is the most popular. In this way, the input parameters and analysis model can have a higher chance to be properly configured to generate accurate results.

3.4 Before-and-After Studies

Before-and-after studies collect data prior to and after a TFI project is implemented to evaluate its mobility and emission impacts. In most cases, the collected mobility data is used in conjunction with emission rates generated by MOVES to estimate emission impacts. In some studies, Portable Emissions Measurement System (PEMS) is used to directly collect emission data. Since before-and-after studies do not rely on any assumptions (e.g., elasticities, program participation rates), they are generally considered to be a more accurate approach than simulation and sketch planning methods for analyzing TFI strategies. However, they also have the following significant limitations:

- Data collection takes a considerable amount of time and effort. Also, the collected data may not well represent the typical traffic conditions due to weather, special events, congestion, incidents, etc.;
- Due to the high cost, many studies only collect data from strategic locations or along major routes. For example, when using PEMS to collect emission data for a traffic signal control project [*92*], only data along the major route was collected. The impacts on minor roads are often ignored or estimated based on simple assumptions; and
- In simulation studies, TFI project impacts can be analyzed under many assumptions and using multiple random seeds, and distributions of various performance measures can be generated to characterize project performance robustness. While for before-and-after studies, because of the prohibiting cost it is almost impossible to collect a large amount of data covering different scenarios to generate performance distributions.

3.5 Summary and Discussion

In this report, the pros and cons of various methods for modeling TFI strategy impacts are analyzed and compared. These methods are broadly categorized into three groups: (1) sketch planning methods; (2) simulation methods; and (3) before-and-after studies.

Sketch planning methods are mostly based on elasticity analysis, pivot-point method, and experience from previous studies to estimate TFI project mobility impacts. Many of them require users to provide assumptions in terms of elasticities and program participation rates, which may have significant impacts on the mobility analysis results. Sketch planning methods mostly rely on the emission rates generated by EMFAC, MOBILE, or MOVES and combine them with the mobility analysis results to estimate emissions. Compared to four-step and activity based travel demand models, sketch planning methods are much simpler and take less time and effort to apply. They can also take induced demand into consideration to some extent.

Simulation methods have been widely used in evaluating transportation projects. They can generate performance distributions that help to assess the robustness of a project's performance. However, coding and calibrating simulation networks can be time consuming. Sometimes they also require user assumptions as the input, particularly for modeling induced demand. This adds uncertainty and affects the accuracy of the modeling results. For evaluating small-scale projects such as intersection traffic signal retiming, induced demand typically is of less concern and in this case computer simulation is usually a good option.

Before-and-after studies are often considered a more reliable approach in evaluating TFI strategies. With before-and-after studies, the induced demand can be implicitly considered if the data collection times and locations are properly chosen. However, this research also identifies some limitations of this approach, including high cost, and incomplete data (due to high data collection cost).

Overall, none of the above methods can well consider long-term mobility and emission impacts. This is because such long-term impacts are heavily affected by many volatile factors such as transportation and energy policies, and vehicle and engine technologies. In fact, it may not be necessary to consider the long-term impacts of certain types of TFI projects. For example, the ITE recommends that traffic signals being retimed every 3~5 years. In this case, considering short-term impacts would be sufficient. For some major capital projects such as grade separation, construction of HOV lanes, and even adding a roundabout, accounting for their long-term impacts (e.g., 10 years) most likely would be necessary but challenging.

4.0 Survey and Results Analysis

The previous two chapters provide an overview of existing Traffic Flow Improvements (TFI) strategies and methods to quantify their impacts. To complement the literature review, this research also conducts a survey to solicit inputs from practitioners from relevant transportation agencies regarding:

- their opinions about the pros and cons of different TFI strategies;
- other promising TFI strategies that they may recommend, but are not included in the literature review result;
- tools/methods they would recommend for quantifying the effects of various TFI strategies;
- how they would rank different TFI strategies; and
- their opinions about quantifying a TFI project's long-term impacts and its impacts on neighboring corridors and induced demand.

4.1 Survey Design

The survey was prepared in the form of a fillable Portable Document Format (PDF) file and was distributed to practitioners within Metropolitan Planning Organizations (MPOs) and the planning and environmental divisions of state Departments of Transportation (DOTs). The survey form and the cover letter are provided in Appendix A. As shown in the survey form, the identified TFI strategies are classified into four broad categories, which are:

- Traffic signalization
- Intersection infrastructure improvements
- Highway control and management
- Road segment (highways and surface streets) infrastructure improvements

In addition, survey respondents are provided with the option to add new TFI strategies not included in any of the above categories.

4.2 Survey Results Analysis

A total of 23 survey forms have been returned, representing agencies in 16 states as shown in Figure 4.1. Note that the survey requests participants to provide their own professional opinions regarding CMAQ TFI strategies, which do not necessarily reflect the official views or positions of their agencies. The results are summarized and presented in the subsections below following the order of the questions in the survey.

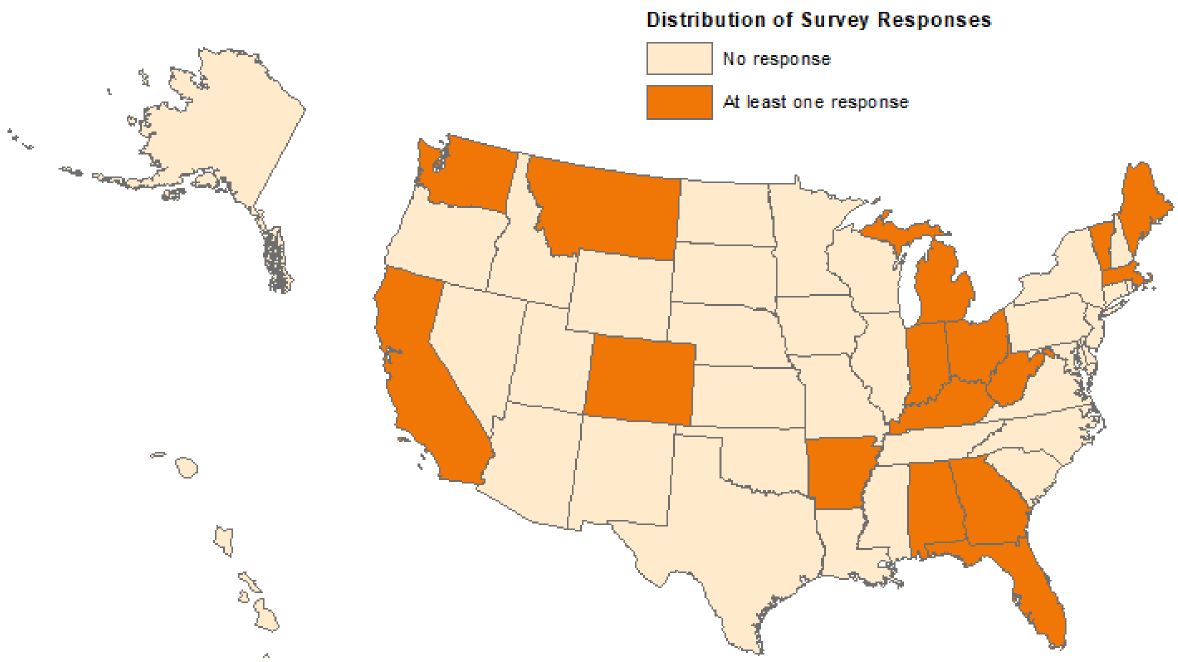

Figure 4.1: Distribution of Survey Responses

4.2.1 Ranking of CMAQ TFI Strategies

Table 4.1 shows how survey respondents rank different TFI strategies in terms of cost-effectiveness, popularity, and number of agencies that have adopted them. The survey differentiates between cost-effectiveness and popularity, since the most widely used or popular strategies may be the least expensive but not necessarily the most cost-effective due to budget constraints. Similarly, the survey also distinguishes a TFI strategy's popularity from the number of agencies that have adopted it.

For each of the columns related to cost-effectiveness or popularity in Table 4.1, the survey asks a respondent to choose three strategies. However, some respondents chose more or less than three strategies in each column and some classified all strategies as either most or least cost-effective/popular. Therefore, adding all the numbers in each column may not be equal to 69 (23 respondents * 3 choices).

As can be seen from Table 4.1, the most cost-effective strategies mirror the most popular strategies. The most cost-effective and most popular strategies are all related to upgrading traffic signal hardware, software, and control plans (i.e., 1a and 1b). Among them, signal re-timing/synchronization (1b) is consistently considered more cost-effective and popular. One interesting finding is about TSP (1c), which is unanimously considered to be one of the least popular and least cost-effective strategies, even by agencies that have adopted TSP. Although this result is a little surprising, it may be justified by the negative impacts of TSP identified in some prior studies [*18*,*22*,*26*,*30*]. Additionally, 21 out of the 23 responding agencies have adopted the upgrading and retiming traffic control strategies, while only 6 of them adopted TSP.

Table 4.1: Ranking of CMAQ TFI Strategies

Strategy	Most cost-effective	Least cost-effective	Most popular	Least popular	# of agencies
1a. Adding/upgrading a traffic signal and associated hardware investment	***11***	3	***14***	1	***21***
1b. Signal re-timing/ synchronization and associated hardware investment	***19***	0	***16***	0	***21***
1c. Transit Signal Priority (TSP) and associated hardware investment	0	***9***	0	***11***	6
2a. Roundabouts (new or conversion into roundabout)	***7***	6	***7***	***7***	***20***
2b. All other intersection geometric improvements (e.g., adding curbs, medians, and turn bays, channelization, pavement resurfacing)	***8***	4	***10***	3	***17***
3a. Managed lanes (e.g., HOT, HOV, reversible, truck only lanes)	2	6	1	***11***	5
3b. Highway/freeway management (variable speed limit, dynamic shoulder lane, ramp meter, investing in highway operations center, etc.)	4	3	1	6	6
3c. Traveler information systems (e.g., dynamic message signs, time to destination display)	5	1	6	4	10
4a. Shoulder paving/widening	2	3	1	6	6
4b. Pavement resurfacing/rehabilitation	4	3	3	5	8
4c. Grade separation (e.g., construction of interchange and overpass)	1	***10***	1	***9***	8
4d. Turn lane (i.e., shared left and right turn lane) and median construction (e.g., closing driveways/intersections)	***8***	3	***8***	2	***18***
4e. Ramp geometric improvements (e.g., extending an acceleration lane)	2	5	1	6	5
5a. Other 1	2	0	1	0	4
5b. Other 2	2	0	1	0	2

Two other cost-effective and popular strategies are intersection geometric improvements other than roundabouts (2b) and turn lane and median construction (4d). Although some respondents gave them unfavorable considerations, overall they rank highly in terms of cost-effectiveness and popularity. These two strategies have also been widely adopted by the responding agencies.

The result for roundabouts (2a) is quite controversial. This probably suggests that roundabouts can be very effective in mitigating congestion and reducing traffic emissions. However, they have to be adopted under appropriate traffic and geometric conditions. Otherwise, their cost-effectiveness can be limited. Despite the controversial opinions about the effectiveness and popularity of roundabouts, they have been adopted by 20 out of the 23 agencies.

In general, managed lanes (3a) and grade separation (4c) are considered cost-ineffective and less popular. This result probably is related mainly to the high costs of such projects, which also explains why few responding agencies have adopted them (see the data in the last column of Table 4.1).

It is worth noting that traveler information systems (3c) has been adopted by 10 responding agencies, which is quite significant compared to other TFI strategies. Its rankings in terms of cost-effectiveness and popularity are also relatively high. Given the prevalence of mobile devices, real-time traffic information becomes increasingly accessible. The potential impacts of traveler information system on mode, route, and departure time choices and eventually congestion and air quality should not be ignored.

The respondents also provide six new TFI strategies. As shown below, some of these strategies can be covered by the existing four categories:

- *Improvements to accommodate pedestrians and bicyclists* – A respondent proposed this strategy but did not choose it as either the most-effective or the most popular one.
- *Installing adaptive traffic control systems and associated hardware* – This can be covered by the existing Category I. Traffic Signalization.
- *Funded capital and software for a traffic management center* – This is covered by Strategy 3b. A respondent proposed it and chose it as one of the most cost-effective and the most popular strategies.
- *Transportation Demand Management Projects* – A respondent proposed this and chosen it as one of the most popular strategies. However, this is often not considered as a TFI strategy.
- *Funded installation of fiber optics for signal connectivity* – A respondent proposed it and chose it as one of the most cost-effective and the most popular strategies. Again, this can be covered by the existing Category I. Traffic Signalization.
- *Diverging Diamond Interchange* – This was proposed and chosen as one of the most popular strategies. It can be included in Category 2b. Diverging diamond interchange has received much attention in recent years but has not seen many implementations in Massachusetts. It would be worthwhile to investigate its applicability here.

4.2.2 CMAQ Quantification Methods

In the survey, respondents are asked to check the tools their agencies are using for quantifying CMAQ TFI strategies. These tools are organized into five main categories as shown in Table 4.2. Also, respondents are given the option (i.e., the "Other" category) to list additional quantification methods.

From the results in Table 4.2, most agencies have their own documented models and/or tools. The research team then followed up with respondents who checked this option to request additional information about their documented models and tools, and the received materials have been reviewed and summarized in Chapter 5. Recommendation. In addition, many responding agencies use computer simulation and models such as MOVES for CMAQ project benefits quantification. Planning models such as 4-step models are also used. Based on the review in Chapter 3, such planning models are often used for major projects covering large areas. In some cases, the assessment of CMAQ strategy benefits are done qualitatively. Under the "Other" category, survey respondents provided some additional quantification methods such as Synchro.

Table 4.2: Method s for Quantifying CMAQ Strategy Benefits

Method	Frequency
1. A set of documented models and/or tools (e.g., Excel spreadsheets)	***17***
2. N/A – assessment is entirely qualitative	3
3. Computer simulation (e.g., VISSIM)	***11***
4. Other tools (e.g., 4-step, activity based, dynamic assignment)	5
5. MOVES or other emission models	***11***
6. Other	--
• *HCM, Synchro, ASSHTO Greenbook Ped/bicycle LOS, Congestion Tool Box*	1
• *Delay studies by driving roads & using bluetooth; Autoturn to ensure safe turning radius, before&after pictures using PTZ cameras*	1
• *Synchro, NPMRDS travel time data, CarteGraph (pavement)*	1
• *STP-eligible project, therefore no quant. benefits required.*	1
• *Other – Not specified*	1

4.2.3 Long-Term Impacts

The summary in Table 4.3 suggests that most agencies (14 out of 23) do consider the long-term impacts of CMAQ TFI projects using various methods either quantitatively or qualitatively. The main reasons for not to consider long-term impacts include: (1) not anticipating significant traffic growth in the future, and (2) not enough time and resources.

For agencies that do consider long-term impacts, they typically

- Utilize travel demand and simulation models (Responses #2, 21, 23) and traffic impact studies (Response #3) to predict future traffic demand and project impacts;
- Simply consider the first year impacts (Response #23);
- Predict the first year impacts and multiply them by project life expectancy (Responses #7, 12);
- Modify the first year travel demand by population growth rate to derive demands and impacts for future years (Response #22); and
- Consider different life expectancies for different types of project (Responses #13, 16). and

Although respondent #15 reported that they do not consider long-term impacts, they assume that a project's effectiveness will degrade over time (due to traffic growth) to zero when a project reaches the end of its effectiveness period, and different types of project are assigned different effectiveness periods. This seems to be a viable framework for modeling the long-term impacts of CMAQ projects.

Additionally, some of the responses in Table 4.3 should be interpreted with caution. This research focuses on the long-term congestion and emissions impacts of traffic flow improvements projects, while some respondents (e.g., #19) may be thinking about the federally required air quality conformity determination, which is required to be undertaken on regional transportation plans that span 20 years and only analyzes capacity-adding projects.

Table 4.3: Long-Term Impacts of CMAQ Projects

ID	Consider long-term impacts?	Reason
1	No	We focus on short-term impacts for these projects.
2	Yes	Using travel demand models, simulations, and traffic/safety analyses software
3	Yes	Before construction of new roadways, new intersections, improvements, developments, etc. a traffic impact study is conducted projecting existing and future traffic volumes for 5 years to evaluate the effects on the existing roadways.
4	Yes	Most projects are on state roadways and cost benefit and life cycle analyses are done.
5	Yes	We see long-term impacts of such traffic improvements to be much more quantitative, due to the adverse effects vehicles (and their emissions) may have on our transportation system. Such things as emission budgets and the pollutants that are associated with mobile sources are key ingredients and how we manage them with the improvements that are being made.
6	No	We don't have any special analysis for traffic flow improvement project applications versus other CMAQ applications, nor (to my knowledge) has any agency in my state evaluated CMAQ traffic flow improvement projects after they are completed.

ID	Consider long-term impacts?	Reason
7	Yes	Annual project impacts are estimated. Short-term benefits are calculated for the first two years of the project by multiplying the annual impacts by two. Long-term benefits are calculated for the first five years of the project by multiplying the annual impacts by five.
8	No	Virtually all of our recent CMAQ project/congestion analyses look at already congested locations, many along corridors that are not expected to show significant traffic growth over the next 20 years. Correspondingly, our CMAQ project evaluation process does not look at projected volumes.
9	No	We do not have or employ the tools to do so due to time and resource constraints. We use the FHWA CMAQ Emissions Calculator Toolkits and diagrams of proposed work/counts for project selection/evaluations. We do consider future year impacts on a qualitative level.
10	No	As an MPO we don’t typically on our own conduct any analysis or modeling. The state DOT in partnership with the state DEP review projects the MPO for air quality impacts and analysis.
11	Yes	--
12	Yes	In each of the former and current non-attainment areas within the state, the MPOs have developed their own methodology for calculating the emissions benefits of CMAQ projects and process for scoring and ranking of projects. In some cases, non-attainment area emissions benefits have been calculated for milestone years based on the anticipated useful life of the project for potential use as credits in the regional conformity analyses, however this has not been necessary and has not been implemented. In other areas the useful life of the project is used in the calculation of cost effectiveness and subsequently ranked to inform the selection process. In some former Non-attainment/ Maintenance Areas MPOs only assess the opening year emissions benefit. They do not use CMAQ emissions benefits for air quality credits in the Regional Conformity Analyses or a projects useful life in the cost effectiveness during the ranking/selection process.
13	Yes	Depends on the project. For major capital improvements we calculate a 20-year project life. For signal synchronization we only calculate 5 years. We quantify all of our emissions reductions.
15	No	We use a project life of five (5) years for signals and signal coordination. Our quantitative methodology was created by the State Air Resources Board. Most sponsors rely on this methodology as an agreed to set of assumptions and methods. The methodology factors in that travel growth degrades project performance over time. Traffic flow improvements that occur immediately after implementation of the project decline to no improvement by the end of the effectiveness period. As a result, the methodology averages speed improvements over the effectiveness period by taking one-half of the first day benefits.

ID	Consider long-term impacts?	Reason
16	Yes	CMAQ TFI projects' project life expectancy is a factor during project selection and is measured quantitatively by kg/yr of emissions reductions using the region's CMAQ emissions calculator. Projects are also considered by cost effectiveness.
17	No	No required federal regulation.
18	Yes	Traffic flow improvements - primarily signal upgrades - are evaluated post implementation for effectiveness and reduction in congestion and wait time. Air quality benefits are not quantitatively evaluated, since these are STP-CMAQ projects, utilizing flexible CMAQ funding.
19	Yes	We primarily address PM10 and CO issues within our MPO area. Our 20-year attainment review period ends in 2022 (CO) and 2025 (PM10), respectively. Promoting projects to provide long-term reduction benefits to maintain our attainment status is our primary focus. In recent years, we have concentrated on traffic light corridor synchronization, paving of alleyways, park and rides, demonstration transit routes, street sweepers, and signalizing installation projects.
20	Yes	--
21	Yes	Assigning the changes to our TDM and running the various years helps us see the impacts the project will have on the network over the years. Can be both quantitatively or qualitatively.
22	Yes	We modify the demand by population growth rate and conduct study with that demand quantitatively to reflect the future scenario.
23	No	We only take into account long-term impacts of projects to the extent they may be regionally significant, and thus go into our Travel Demand Model. Otherwise, the emissions calculations we perform are only relevant for their first obligation year, when state DOT considers their emissions benefits to take effect.

4.2.5 Impacts on Adjacent Parallel Corridors or Areas

Compared to long-term impacts, less agencies (8 out of 23 as in Table 4.4) take the impacts on neighboring corridors into consideration. Even if they do, some of them (Respondents #1, 4, 5) only qualitatively consider such impacts using methods such as public hearings. For quantitative analysis, agencies mainly rely on regional travel demand models (Respondents #2, 20). Also, it is noted that regional impacts are often not done just for a single CMAQ project unless it is regionally significant (Respondents #4, 23), as preparing travel demand models for such analyses is time consuming. Overall, the survey result suggests that regional impacts are usually done for large CMAQ projects with significant regional impacts using travel demand models. For small CMAQ projects, a traffic impact study may better meet the needs (see Respondent #3).

Table 4.4: Impacts of CMAQ Projects on Adjacent Parallel Corridors or Areas

ID	Consider neighboring areas?	Reason
1	Yes	In our application for these types of projects, impacts must be identified and are considered qualitatively during the selection process.
2	Yes	Using travel demand models to evaluate multi modal impacts and a set of criteria to score projects.
3	Yes	Before construction of new roadways, new intersections, improvements, developments, etc. a traffic impact study is conducted projecting existing and future traffic volumes for 5 years to evaluate the effects on the existing roadways.
4	Yes	Usually these type projects involve public hearings and most input is qualitative even though traffic models are used for informational and visual display.
5	Yes	Yes, when air quality conformity is monitored, modeled and maintained we do so regionally, not per project. Therefore, other corridors and neighboring areas are covered under such qualitative analysis.
6	No	--
7	No	The tools we use do not support analysis of parallel corridors.
8	No	Our MPO's regional traffic model was not created at the level of detail needed to facilitate such an analysis. We are now relying on state DOT's Statewide Traffic Model to forecast traffic volumes on our region's key roadways and this model has similar limitations.
9	No	We do not have or employ the tools to do so due to time and resource constraints. We use the FHWA CMAQ Emissions Calculator Toolkits and diagrams of proposed work/counts for project selection/evaluations. We do consider impacts om adjacent parallel corridors and neighboring areas on a qualitative level.
10	No	The answer "no we don't" is applicable for all following questions. As an MPO we don't typically on our own conduct any analysis or modeling. The state DOT in partnership with the state DEP review projects the MPO for air quality impacts and analysis.
11	No	--
12	No	Simplicity
13	No	We don't explicitly do that, although we do like to confirm that projects are consistent with our regional plans.
15	No	It's the same reason as in question #3 (see Response #15 in Table 4.3), our quantitative methodology was created by the state Air Resources Board. Most sponsors in our state rely on this methodology as an agreed to set of assumptions and methods.
16	Yes	When calculating the emissions reduction of a CMAQ TFI project better public route choice and the impacts on adjacent corridors is factored in.
17	No	No required federal regulation.

ID	Consider neighboring areas?	Reason
18	No	Traffic flow improvements - primarily signal upgrades - we try to improve the traffic flow on our corridors so that traffic will stay on the main route and not use neighboring streets. With our traffic flow improvement projects we are optimizing the traffic signal timings to reduce stops and delays along our corridors.
19	Yes	Our metropolitan region will begin construction of a new arterial corridor that will run parallel to the Central Business District (long dealing with CO reduction efforts). While no CMAQ funds were used in the design or construction of this new parallel arterial, there are air quality benefits resulting from its construction. However, in general practice, each project is submitted by the respective jurisdiction based on their individual needs and prioritized based on most air quality in comparison to other submitted applications.
20	Yes	Our state DOT uses its Statewide Travel Demand Model, sometimes using select link analysis, depending on the anticipated scope of the project.
21	No	CMAQ project are site specific, and it would be difficult quantifying its impacts on other areas.
22	No	It depends on which analysis we do for the project. If we do macro-simulation, the answer would be yes. If we do micro-simulation, the answer would be no, because it is costly to build a micro-simulation model for all adjacent parallel corridors and neighboring areas.
23	No	Same explanation as number 3 above (see Response #23 in Table 4.3). Also, we do not feel we have the adequate tools to reliably measure the emissions impacts on parallel corridors or neighboring areas unless the projects are regionally significant (i.e., a scope that can be put into our travel demand model).

4.2.5 Impacts of Induced Demand

The results in Table 4.5 show that very few responding agencies (2 out of 23) take induced demand into consideration when quantifying the benefits of CMAQ TFI projects. The main reasons include: (1) no clear and well-accepted methods and tools, (2) the question itself is too complicated, and (3) not enough resources. For the two agencies that do consider induced demand, one reported using travel demand models and the other one did not provide any details. Overall, the impacts of induced demand on a CMAQ project's potential benefits have been given less attention compared to the long-term impacts and impacts on neighboring areas/corridors, probably because of the subtle and complicated nature of induced demand and the difficulty to reliably model its impacts. Another possible reason is that some responding agencies implicitly consider induced demand when modeling the long-term impacts (e.g., Response #15 in Table 4.3) and impacts on adjacent corridors (e.g., Response #2 in Table 4.4).

Table 4.5: Impacts on Induced Demand

ID	Consider induced demand?	Reason
1	No	We focus on the air quality emissions benefits.
2	Yes	Most by regional travel demand model
3	No	We currently have a problem where there is no room for widening existing roadways and very little room for new roadways. The biggest contributing factor to congestion within our county is increase due to growth & development which will force us to evaluate more intelligent solutions in the future.
4	No	Complicated analysis that is so variable that there seems to be no real conclusive results and very opinionated.
5	Yes	Yes, benefits toward better air quality for our region.
6	No	--
7	No	Lack of guidance/standard approach.
8	No	Similar to the response to Question 4 (see Response #8 in Table 4.4), our MPO has limited ability to quantify changes to travel demand that would be triggered by the completion of a CMAQ project. This would include possible mode shifts that could occur by reducing congestion at a key intersection or along a key section of arterial roadway in the region.
9	No	We do not have or employ the tools to do so due to time and resource constraints. We use the FHWA CMAQ Emissions Calculator Toolkits and diagrams of proposed work/counts for project selection/evaluations. We do consider induced demand on a qualitative level.
10	No	The answer "no we don't" is applicable for all following questions. As an MPO we don't typically on our own conduct any analysis or modeling. The state DOT in partnership with the state DEP review projects the MPO for air quality impacts and analysis.
11	No	--
12	No	No methodology developed.
13	No	It's not a standard practice in our projects, nor is there a clear, accepted way to calculate this.
15	No	It's the same reason as in question #3 (see Response #15 in Table 4.3), our quantitative methodology was created by the state Air Resources Board. Most sponsors in our state rely on this methodology as an agreed to set of assumptions and methods.
17	No	No required federal regulation.
18	No	Primarily our projects are addressing areas where we have existing congestion and we are just trying to optimize the flow of traffic to the best of our ability.
20	No	We are not yet that selective. Our current approach has been identifying eligible CMAQ projects. Since we now have CMAQ performance targets, we will be improving our analysis tools.
21	No	CMAQ project are site specific, and generally don't produce and additional demand in an area.

ID	Consider induced demand?	Reason
22	No	It depends which analysis we do for the project. If we do macro-simulation, the answer would be yes. If we do micro-simulation, the answer would be no.
23	No	Same explanation as number 4 above (see Response #23 in Table 4.4).

4.2.6 Challenges and Recommendations

Table 4.6 lists the main challenges brought up by survey respondents and their recommendations. The main challenges are summarized below:

- Major obstacles mentioned by multiple respondents to CMAQ project benefits quantification include lack of resources (e.g., funding, experienced staff, reliable data), well-accepted and documented tools/models (e.g., a look up table), and consistent and widely-used evaluation standards;
- There is a lack of project post evaluations and “apples to apples” comparisons. Most CMAQ project benefits are estimated using various methods and based on different assumptions. It is difficult to compare these results directly and rank candidate projects;
- Local agencies often are not motivated to invest in CMAQ project benefits quantifications, particularly those detailed analyses such as long-term impacts and impacts of induced demand, which are not required by federal and local regulations; and
- There are many restrictions on how to use CMAQ funds. Due to these restrictions and limited funds, sometimes projects with the most benefits do not get selected.

To address the above issues, the survey respondents provided valuable suggestions, which are summarized below:

- Encouraging and facilitating collaboration among transportation agencies for sharing data, quantification methods, and thoughts so that the best practices and successful experience can be identified, further improved, and adopted by other agencies;
- CMAQ project benefits may change over time due to factors such as changes in traffic compositions (e.g., electric vehicles). Such factors should be considered in CMAQ project benefits quantification;
- The potential benefits of a CMAQ TFI project can be site-specific. It is important to choose the right strategy for the right site. Also, it is recommended to use a data-driven approach (e.g., data from Traffic Management Center) to rank project sites and to compare site performances before and after a project;
- Taking into consideration the congestion and air quality benefits of nonmotorized transportation modes; and
- Expanding the FHWA CMAQ Emissions Calculator Toolkit and providing clearer explanation for each tool.

Table 4.6: Challenges and Recommendations

ID	Challenges and Recommendations
1	**Challenges**: Lack of experienced staff to perform technical analysis. **Recommendations**: None.
2	**Challenges**: Mainly no post evaluation **Recommendations**: Impacts and benefits on quantity and quality of nonmotorized transportation
3	**Challenges**: The greatest challenge is to be able to quantify the effects of improvements/modifications. A good example is the recent upgrade of signal controllers/central software in my county. Over 200 traffic signal controllers were upgraded within the past year and the central software was upgraded from a 10+ year old system. While we anecdotally can say that the upgrade has been a great success and has helped reduce travel time/delays within the county, there is no surefire way to put report that accurately. **Recommendations**: The best way to resolve the lack of data is a network-wide system that will give real-time volumes, travel times, travel routes, etc. that will record historical data and report back to the TMC. With this data, the TMC will know when and where problems arise and be able to relieve congestion immediately through timing, informing drivers of alternate routes, etc. and be able to record the effects of changes made through timing, improvements, etc.
4	**Challenges**: CMAQ funds use are so limited that projects with the highest potential for example adding capacity at a very congested location to improve major delays is considered ineligible yet a bike/pedestrian path is acceptable even though its emissions reductions are much less. We wanted to use CMAQ funds to help build an overpass over a railroad that splits one of our communities down the middle and blocks every crossing in the City consistently during all hours with some delays up to an hour being recorded. We were turned down on using CMAQ funds even though it would have been one of the highest emission reduction projects in our TIP. **Recommendations**: Use CMAQ Funds where you get the most local emission reductions.
5	**Challenges**: Funding is always number one in challenges, but a few others may be coordination efforts with other agencies, reliable data and validation of such data. **Recommendations**: Better coordination with others to share ideas and thoughts, so the best methods can be used toward improving traffic flow in congested area.
6	**No response provided.**
7	**Challenges**: One of the main issues is lack of comparability across communities and project types when data inputs are estimated using different approaches. The benefits are calculated prior to project implementation, so the level of impact is an estimate. **Recommendations**: None.
8	**Challenges**: The main problems we see are 1) the fact that there are very few post evaluations being undertaken, and 2) there is no widely accepted selection of evaluation measures or criteria. Our DOT's CMAQ project evaluation process does look at the dollar cost associated with each 1KG of emissions reductions, but there may be better or additional measures that could/should be used. **Recommendations**: None.

ID	Challenges and Recommendations
9	**Challenges**: The main challenges we face are lack of consistent tools and skill sets from local agencies though out the state, as well as time and resource constraints. **Recommendations**: The mandatory use of Synchro models for analysis.
10	**No response provided.**
11	**No response provided.**
12	**Challenges**: Limited project specific data available prior to project initiation and funds being available. **Recommendations**: Many of the benefits from some types of projects such as an intersection signalization or geometric improvements are very small and as cars become much cleaner will be reduced over time. It would be helpful to have an average emission benefit that applied based on a general project type. such as a lookup table. (i.e., left turn lane only, right and left turn lane, signalization based on intersection configuration), or a set of standard assumptions for inputs (i.e. average speed improvement from corridor signalization, peak hour delay factor for intersection improvements, average delay reduction based on future configuration)
13	**Challenges**: I would like more accepted, standard methodologies to use. It seems like there are too many, nothing official, and some project types are hard to quantify. It would be nice to have quantification methods made available by DOTs or some other agency. **Recommendations**: In my state, the entire focus of the program is on emissions reductions. While they are extremely important, there is very little done in the Congestion Mitigation part of the CMAQ program. I would like to see some example quantifications of congestion improvements, apart from emissions reductions. I'm not sure what they would be based on-time delay, volume to capacity, ... ?
14	**No response provided.**
15	**Challenges**: We are using an old methodology that hasn't been refreshed since 2005. We don't do post evaluation. **Recommendations**: I would only add that, in my personal opinion, HOT lanes and anything that prices transportation congestion, if done well, would be super cost effective. That said, our region has not yet done such a project.
16	**Challenges**: Lack of reliable data, no post evaluation, and obtaining correct data for "apples to apples comparison" are the main problems. **Recommendations**: before and after analysis, public survey of perceived benefits.
17	**No response provided.**
18	**Challenges**: Since we use flexible STP-CMAQ funding, there is not a requirement to quantify air quality benefits for these projects. **Recommendations**: Since we use flexible STP-CMAQ funding, there is not a requirement to quantify air quality benefits for these projects.
19	**Challenges**: My MPO is primarily surrounded by mountain ranges that creates a geographic "bowl". This bowl is a perfect condition that causes inversions that stagnates our region's ability to clear out our area like most other metropolitan areas. Our ability to retain our attainment levels when combating these inversion conditions, all while supporting a predominately agricultural based region is being able to accurate track the post construction benefits in our region. **Recommendations**: None.

ID	Challenges and Recommendations
20	**Challenges**: We currently use the output from our statewide travel demand model to determine the delta for any given treatment. We are now beginning to look at other tools to help validate our processes. **Recommendations**: None.
21	**Challenges**: There is no clear procedure / guidance on how to evaluated all every potential CMAQ projects, so assumptions must be made and processes must be created. **Recommendations**: It would be great if a broader list procedures / processes be created to help with the CMAQ evaluations.
22	**Challenges**: No standardized systematic methodology for evaluation of each type of project. **Recommendations**: Give standardized systematic methodology and detailedly documented examples so that individual organizations can easily follow.
23	**Challenges**: The main problems/challenges we have faced have to do with a lack of reliable tools published or provided to us. This is starting to improve as evidenced by the CMAQ Emissions Calculator Toolkit (https://www.fhwa.dot.gov/environment/air_quality/cmaq/toolkit/index.cfm). Also, there simply are not enough incentives for us to spend the resources necessary to improve the emissions modeling of CMAQ projects beyond the state DOT requirement of estimating the emissions in the first proposed obligation year. **Recommendations**: I would recommend FHWA further refine the CMAQ Emissions Calculator Toolkit to include more traffic flow improvement project types such as grade separations and a clearer explanation of the inputs that would be project applicants, many of which do not have professionally trained engineers on staff, can reference.

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5.0 Recommendations

This chapter concludes this study by providing recommendations to assist MassDOT with improving its current CMAQ TFI program practices. It consists of two sections. Section 5.1 provides some high-level recommendations related to MassDOT's main concerns such as long-term, regional, and induced demand impacts; and Section 5.2 presents specific recommendations organized by the main categories of CMAQ TFI strategies for MassDOT to consider.

5.1 Overall Recommendations for Quantifying TFI Strategies

5.1.1 Long-Term Impacts

A project's long-term impacts should take into consideration its life expectancy, future traffic demand, and future traffic characteristics. Some studies do account for a project's life expectancy and multiply it by the project's first year benefits for cost-effective analysis. However, it is also important to model the changes of a project's effectiveness over time, due to traffic growth, traffic redistribution, etc. A practical solution is to consider that a project benefits will decrease linearly to zero when its life expectancy is reached, and different types of project should be assigned different life expectancies based on prior experience. For example, the ITE recommends that traffic signals be retimed every 3~5 years.

For projects that are likely to have a long life expectancy, such as grade separation and construction of HOV lanes, it is important to also consider factors such as transportation and energy policies, and vehicle and engine technology advancements. For example, changes in fuel efficiency standards, electric vehicle subsidy policies, and engine technologies may significantly affect future traffic compositions and a TFI project's effectiveness. Also, shared mobility and other new mobility solutions may reduce vehicle trips but increase short-distance nonmotorized trips. In such cases, the above linear degradation assumption should be re-examined.

5.1.2 Regional and Induced Demand Impacts

Estimating regional and induced demand impacts is very complicated, since it involves the modeling of route, mode, and even departure time choices. As suggested by the survey results, compared to long-term impacts, less responding agencies take regional impacts into account. Very few of them consider induced demand. Aside from the complexity reason, it may not be necessary to consider the regional and induced demand impacts for some types of CMAQ TFI project, particularly projects that only affect one or two intersections. For projects such as managed lanes and highway/freeway traveler information systems, modeling the regional and induced demand impacts may be essential.

The regional and induced demand impacts tend to be site specific, and are usually modeled using regional demand models and sketch planning tools. Applying regional demand models takes a considerable amount of time and effort, and the accuracy of the results also depends heavily on the quality of the input data and various assumptions. Unless it is for a major project (e.g., HOV lanes), sketch planning tools are recommended.

5.1.3 Quantification Tools

Although the literature review has identified many TFI quantification methods (see Chapter 3), many of the methods are either obsolete or not being maintained for many years. Nevertheless, the review results can help state DOTs develop new quantification tools. Many state DOTs have developed their own sets of quantification methods covering a few TFI categories. For example, the existing MassDOT CMAQ project benefits quantification toolset covers intersection improvements and TSP. Although these methods developed by different state DOTs are more or less similar, their results cannot be directly compared due to different assumptions and models. Much of the TFI benefits data in the FHWA CMAQ database is estimated using these methods. Therefore, such data cannot be compared to reliably rank TFI strategies as well.

It is recommended that MassDOT review the tools developed by other states and further improve and expand its current CMAQ TFI toolset. FHWA has developed a CMAQ Emissions Calculator Toolkit, which covers a very limited number of TFI strategies. Nevertheless, MassDOT should consider adopting the FHWA Toolkit. It would be beneficial if FHWA can continue to expand the Toolkit, and further establish an annual forum for state DOTs to share their experience with CMAQ benefits quantification. Such a forum may facilitate the expansion of the FHWA Toolkit and the development of a set of standard performance measures for comparing different TFI strategies. Besides standardizing TFI quantification methods, using the same set of performance measures is also very important to facilitate project comparison. At this forum, best practices for each category of TFI can be shared and technical trainings can be provided.

For some TFI projects (e.g., signal retiming), it might be easier to model their impacts using microscopic simulation. Even for those that can be modeled by existing MassDOT Excel Spreadsheet tools, simulation analyses are often still needed to generate the inputs required by the Excel tools. Therefore, it would be beneficial to have some guidelines for conducting the simulation analyses to ensure consistency and the quality of the input data to the Excel tools.

Finally, existing quantification tools mainly focus on congestion and air quality impacts. Since traffic accidents also attribute significantly [*93*] to traffic congestion and emissions, it might be beneficial to also consider a TFI project’s safety impacts, particularly those corridor-level projects (e.g., arterial signal coordination, resurfacing a long highway segment). While it would be interesting to do so, no agencies have been found to consider the CMAQ benefits of improved safety in practice.

5.1.4 Local Factors

Factors such as emission rates and truck percentages play an important role in quantifying the benefits of TFI projects. Whenever possible, local factors should be considered in the quantification analysis. A local factor database can be created and shared with all local planning agencies. In some cases, it might be necessary to develop local factors for different parts of Massachusetts if the differences among them are significant enough.

5.1.5 Research and Workforce Development

From the survey results, the top two obstacles to TFI strategy modeling are: (1) lack of resources (e.g., funding, experienced staff, reliable data), well-accepted and documented tools/models (e.g., a look up table), and consistent and widely-used evaluation standards; (2) lack of project post evaluations and "apples to apples" comparisons. Some of these issues have been addressed in previous recommendations. For the remaining ones, additional resources and workforce development are the key. It is recommended that MassDOT invest additional resources in staff training and professional developments. Additionally, more research is needed. Unlike the current research that focuses on reviewing the status of CMAQ TFI strategy benefits quantification, future research should concentrate on developing specific CMAQ quantification tools/procedures for each TFI category that can accurately consider long-term, regional, and induced demand impacts.

5.1.6 Before-and-After Study

The literature review and survey results suggest that very few before-and-after studies have been conducted to quantify the impacts of TFI projects, due to the high costs and the tremendous amount of efforts typically required in the data collection. However, it is important to collect field data to validate the aforementioned quantification methods. To bridge this gap, MassDOT should investigate alternative data collection approaches for before-and-after studies.

One possible solution is to use data from crowdsourcing platforms, connected vehicles, and traffic management centers [*94*,*95*] to continuously monitor traffic operations before and after a project. Also, such data can be utilized to identify and rank bottlenecks, and potentially to suggest the best TFI strategies.

Although there is some general consensus about the cost-effectivenesses of various TFI strategies, whether a project can be successful depends largely on site specific characteristics. In other words, transportation agencies should choose TFI strategies not solely based on their rankings, but also their applicability to a particular project site. Using the detailed data collected from new sources and advanced algorithms such as machine learning, MassDOT may be able to identify and compare a group of similar intersections/corridors with different control settings, and use the comparison result to suggest TFI solutions. Such a data-driven approach may potentially generate more robust performance.

5.2. Recommendations for Improving MassDOT TFI Strategy Quantification Tools

The recommendations in this section are organized according to the TFI strategies listed at the beginning of Chapter 2. The main purpose is to provide specific suggestions for MassDOT to improve its current Excel spreadsheet based CMAQ TFI analysis tools. Among the twelve TFI strategies, MassDOT now only has quantification tools to evaluate intersection improvements and TSP strategies.

5.2.1 Intersection Improvements

The current MassDOT tools can be used to model improvements for individual intersections such as geometric improvements, signalization, and conversion into a roundabout. These tools are quite generic, and require additional tools (e.g., simulation) to provide the inputs (e.g., delay) they need. It might be helpful to incorporate additional modules into them and create more specific tools for different TFI strategies.

For example, for *intersection signalization and retiming*, the FHWA CMAQ emissions calculator toolkit includes an Excel spreadsheet tool with delay calculation embedded in it. The delay calculation module is based on procedures in the Highway Capacity Manual. Such an integrated tool streamlines the emission analysis and avoids the need for another delay calculation tool. MassDOT can either adopt the FHWA tool or modify its own spreadsheet tools by adding a delay calculation module. By integrating different delay calculation modules, specific tools can be created for various TFI strategies.

Alternatively, MassDOT can develop a lookup table (similar to what NCTCOG has done) and use it in conjunction with its current intersection analysis tools. The lookup table provides the anticipated delay reductions for each TFI strategy and saves the trouble of using delay calculation models. MassDOT can either borrow the lookup table prepared by other states or develop its own table. Developing such a table would require a lot of data from local before-and-after studies, but can generate more accurate results.

For *signal synchronization* projects, MassDOT does not have a dedicated quantification tool. Instead, they use the same tool for individual intersections. With a long arterial, inputting data alone can be a time-consuming task. It is recommended that MassDOT develop tools to automate the process of transferring data from traffic signal synchronization models into their intersection quantification tool. Also, MassDOT may want to consider using the signal synchronization tool in the FHWA CMAQ emissions calculator toolkit, which takes arterial travel time savings into account.

For *roundabouts*, MassDOT uses its existing intersection improvement evaluation tool. As discussed above, MassDOT may choose to integrate a roundabout delay calculation module into it or develop a lookup table as in the NCTCOG (master table-based spreadsheets) and FIXiT 2.0 (detailed master table) models. MassDOT may also consider the roundabout tool in the CMAQ emissions calculator toolkit and the ME-CMAQ package to further improve their intersection quantification tool.

The current MassDOT tools (for both intersection improvements and TSP) only calculate the project cost-effectiveness for the build year. It is recommended that MassDOT modify the tools and calculate long-term cost-effectiveness considering capital recovery factor and project life expectancy. Other than the recommended approaches in Section 5.1.1, a short-term solution is to follow the method in the ME-CMAQ manual.

5.2.2 Managed Lanes and Traveler Information Systems

For *managed lanes*, the NCTCOG has developed an Excel spreadsheet to estimate the emission benefits of constructing or expanding HOV facilities. It considers the running exhaust emissions due to speed changes in both HOV and general purpose lanes, and vehicle trip reductions. The methods used in this tool are well documented and the key inputs and outputs can be found in Table 3.2. This can be used as the basis for MassDOT to develop its own managed lanes quantification tool.

No analytical quantification tools or methods were identified for *Traveler Information Systems*. MassDOT is encouraged to consider a before-and-after study quantification approach for this type of TFI project, using crowdsourced data, etc. MassDOT can also use the FIXiT 2.0 tool (e.g., the master table approach).

5.2.3 Shoulder, Pavement, and Turn Lanes

No analytical tools were found for quantifying *shoulder widening or paving* projects. Some studies (in the master table of FIXiT 2.0) suggest that the temporary use of shoulder could increase highway capacity by 7%-22% and reduce travel time by 27%-34%. MassDOT again could adopt the before-and-after study and the lookup table approaches. Both methods would benefit from a large set of relevant historical data, and data from nontraditional sources such as crowdsourcing can potentially be very helpful in this case.

For *pavement surfacing* projects, MassDOT may consider adopting the ME-CMAQ method. Its main inputs include project length, ADT, number of access points to be paved, etc. The emission factors for various unpaved/paved roads are given but can be calibrated using Massachusetts data.

For *turn lanes and median construction* projects, the ME-CMAQ tool can be used to calculate emissions reductions and cost-effectiveness. However, it requires users to provide delays before and after project. Such information can be estimated using tools such as HCM and Synchro. They may also be estimated using the master table of FIXiT 2.0, which provides the percentages of delay reductions and capacity increases.

5.2.4 Others

For all remaining TFI strategies, no analytical tools or methods were found to quantify their impacts. MassDOT may adopt the master table approach in FIXiT 2.0 and collect local data to develop its own master table. In the long term, it would be very helpful if the benefits data in the FHWA CMAQ database can be marked as estimated or observed, and additional project information (e.g., areas covered) can be provided. In this way, national and regional master tables can be more easily developed for various TFI strategies using information in this database.

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7.0 Appendices

7.1 Appendix A: Survey Cover Letter and Survey Form

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November 26, 2018

RE: Congestion Mitigation and Air Quality Improvement (CMAQ) Traffic Flow Improvements Strategies and Quantification Methods

To whom it may concern,

Our research team is conducting a study on CMAQ Traffic Flow Improvements Strategies funded by SP&R research funding through the Massachusetts Department of Transportation (MassDOT). As part of this study, we are conducting a survey for the benefit of MassDOT and other state departments of transportation/MPOs to: (1) compile a comprehensive list of cost-effective CMAQ Traffic Flow Improvements strategies, and (2) to identify models and tools for quantifying the benefits of these strategies.

This survey, in the form of a fillable PDF file, consists of 8 questions and should take less than 20 minutes to complete. It is only intended for the research purposes mentioned above. We identified you as an expert in this area. We will not disclose the contact information of any participant. The collected data will be summarized and shared with all survey participants.

Once you complete the survey, please save and email the PDF file to yuanchang_xie@uml.edu directly. If you have any questions regarding this survey, please feel free to contact me either by phone or email. Thank you very much in advance for your participation and time.

If there are questions about this research project, you may reach out to the MassDOT Research Project Champion: Derek Krevat at (857) 368-8868, or derek.krevat@dot.state.ma.us.

Sincerely,

Yuanchang Xie

Yuanchang Xie, PhD, PE
Associate Professor

A Survey on CMAQ Traffic Flow Improvements (TFI) Strategies and Quantification Methods

1. For CMAQ Traffic Flow Improvements (TFI) strategies in the 1st column, please check those that your agency has implemented before. In the 2nd column, please check a method if it has been used by your agency to quantify the impacts of one or more checked strategies in that category.

CMAQ Traffic Flow Improvements (TFI) Strategies **(Check ALL strategies that have been implemented by your agency)**	**Quantification Methods (Check ALL methods that have been used by your agency for each category on the left)**
Category 1. Traffic Signalization ☐ 1a. Adding/upgrading a traffic signal and associated hardware investment ☐ 1b. Signal re-timing/synchronization and associated hardware investment ☐ 1c. Transit Signal Priority (TSP) and associated hardware investment	☐ a set of documented models and/or tools (e.g., Excel spreadsheets) ☐ N/A – assessment is entirely qualitative ☐ computer simulation (e.g., VISSIM) ☐ other tools (e.g., 4-step, activity based, dynamic assignment) ☐ MOVES or other emission models ☐ other (please specify ______________)
Category 2. Intersection Infrastructure Improvements ☐ 2a. Roundabouts (new or conversion into roundabout) ☐ 2b. All other intersection geometric improvements (e.g., adding curbs, medians, and turn bays, channelization, pavement resurfacing)	☐ a set of documented models and/or tools (e.g., Excel spreadsheets) ☐ N/A – assessment is entirely qualitative ☐ computer simulation (e.g., VISSIM) ☐ other tools (e.g., 4-step, activity based, dynamic assignment) ☐ MOVES or other emission models ☐ other (please specify ______________)
Category 3. Highway Control and Management ☐ 3a. Managed lanes (e.g., HOT, HOV, reversible, truck only lanes) ☐ 3b. Highway/freeway management (variable speed limit, dynamic shoulder lane, ramp meter, investing in highway operations center, etc.) ☐ 3c. Traveler information systems (e.g., dynamic message signs, time to destination display)	☐ a set of documented models and/or tools (e.g., Excel spreadsheets) ☐ N/A – assessment is entirely qualitative ☐ computer simulation (e.g., VISSIM) ☐ other tools (e.g., 4-step, activity based, dynamic assignment) ☐ MOVES or other emission models ☐ other (please specify ______________)
Category 4. Road Segment (highways and surface streets) Infrastructure Improvements ☐ 4a. Shoulder paving/widening ☐ 4b. Pavement resurfacing/rehabilitation ☐ 4c. Grade separation (e.g., construction of interchange and overpass) ☐ 4d. Turn lane (i.e., shared left and right turn lane) and median construction (e.g., closing driveways/intersections) ☐ 4e. Ramp geometric improvements (e.g., extending an acceleration lane)	☐ a set of documented models and/or tools (e.g., Excel spreadsheets) ☐ N/A – assessment is entirely qualitative ☐ computer simulation (e.g., VISSIM) ☐ other tools (e.g., 4-step, activity based, dynamic assignment) ☐ MOVES or other emission models ☐ other (please specify ______________)
Category 5. Other CMAQ Traffic Flow Improvements (TFI) Strategies you would recommend ☐ 5a. (add description) ☐ 5b. (add description)	☐ a set of documented models and/or tools (e.g., Excel spreadsheets) ☐ N/A – assessment is entirely qualitative ☐ computer simulation (e.g., VISSIM) ☐ other tools (e.g., 4-step, activity based, dynamic assignment) ☐ MOVES or other emission models ☐ other (please specify ______________)

A Survey on CMAQ Traffic Flow Improvements (TFI) Strategies and Quantification Methods

2. Please rank the following CMAQ Traffic Flow Improvements (TFI) Strategies. Pick three (3) from each column below.

CMAQ Traffic Flow Improvements (TFI) Strategies	3 most and least cost-effective		3 most and least commonly-used	
Category 1. Traffic Signalization				
1a. Adding/upgrading a traffic signal and associated hardware investment	☐Most	☐Least	☐Most	☐Least
1b. Signal re-timing/synchronization and associated hardware investment	☐Most	☐Least	☐Most	☐Least
1c. Transit Signal Priority (TSP) and associated hardware investment	☐Most	☐Least	☐Most	☐Least
Category 2. Intersection Infrastructure Improvements				
2a. Roundabouts (new or conversion into roundabout)	☐Most	☐Least	☐Most	☐Least
2b. All other intersection geometric improvements (e.g., adding curbs, medians, and turn bays, channelization, pavement resurfacing)	☐Most	☐Least	☐Most	☐Least
Category 3. Highway Control and Management				
3a. Managed lanes (e.g., HOT, HOV, reversible, truck only lanes)	☐Most	☐Least	☐Most	☐Least
3b. Highway/freeway management (variable speed limit, dynamic shoulder lane, ramp meter, investing in highway operations center, etc.)	☐Most	☐Least	☐Most	☐Least
3c. Traveler information systems (e.g., dynamic message signs, time to destination display)	☐Most	☐Least	☐Most	☐Least
Category 4. Road Segment (both highways and surface streets) Infrastructure Improvements				
4a. Shoulder paving/widening	☐Most	☐Least	☐Most	☐Least
4b. Pavement resurfacing/rehabilitation	☐Most	☐Least	☐Most	☐Least
4c. Grade separation (e.g., construction of interchange and overpass)	☐Most	☐Least	☐Most	☐Least
4d. Turn lane (i.e., shared left and right turn lane) and median construction (e.g., closing driveways/intersections)	☐Most	☐Least	☐Most	☐Least
4e. Ramp geometric improvements (e.g., extending an acceleration lane)	☐Most	☐Least	☐Most	☐Least
Category 5. Other CMAQ Traffic Flow Improvements (TFI) Strategies you would recommend				
5a. (Linked to page 1 no need to change)	☐Most	☐Least	☐Most	☐Least
5b. (Linked to page 1 no need to change)	☐Most	☐Least	☐Most	☐Least

3. In your CMAQ Traffic Flow Improvements (TFI) project selection/evaluation, do you consider the **long-term (>= 5 years) impacts** of a project?

   ☐ Yes, we do ☐ No, we don't

   If yes, could you briefly describe how you take such impacts into consideration, including a description of whether you do so quantitatively or qualitatively?

   If not, what are the reasons?

4. In your CMAQ Traffic Flow Improvements (TFI) project selection/evaluation, do you consider a project's **impacts on adjacent parallel corridors or neighboring areas**?

   ☐ Yes, we do ☐ No, we don't

   If yes, could you briefly describe how you take such impacts into consideration, including a description of whether you do so quantitatively or qualitatively?

   If not, what are the reasons?

A Survey on CMAQ Traffic Flow Improvements (TFI) Strategies and Quantification Methods

5. In your CMAQ Traffic Flow Improvements (TFI) project selection/evaluation, do you consider the **impacts of induced demand** on a project's potential benefits?

   ☐ Yes, we do ☐ No, we don't

   If yes, could you briefly describe how you take such impacts into consideration, including a description of whether you do so quantitatively or qualitatively?

   If not, what are the reasons?

6. What are the **main problems/challenges** (e.g., lack of reliable data, cost, no post evaluation) you have experienced in quantifying the benefits of CMAQ Traffic Flow Improvements (TFI) projects?

7. What approaches or **new methods** would you recommend for evaluating the benefits of CMAQ Traffic Flow Improvements (TFI) projects?

8. Would you like to receive a copy of the summarized survey result?

   ☐ Yes ☐ No