Texas A&M Transportation Institute

Potential Use of Ramp Metering as Congestion Management Strategy in the Dallas-Fort Worth Metroplex

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16. Abstract

There is an increasing interest by public officials in the use of ramp metering for congestion mitigation at various freeway locations in the Dallas-Fort Worth (DFW) metroplex. DFW is currently in nonattainment for ground-level ozone, and transportation improvements in the area are subject to transportation conformity process. This project used dynamic traffic assignment and microscopic simulation models to evaluate the impacts of ramp metering on traffic conditions in two DFW corridors, selected using existing vehicle probe data. The project also assessed impacts of ramp metering on air quality by applying DFW-specific emissions rates to outputs from the simulation models. Results show that ramp metering can help improve operations of congested freeways without adversely affecting air quality in corridors where the cause of congestion is primarily from these ramps. Ramp metering with queue flush operation is the recommended strategy.

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POTENTIAL USE OF RAMP METERING AS CONGESTION MANAGEMENT STRATEGY IN THE DALLAS-FORT WORTH METROPLEX

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer (researcher) in charge of the project was Nadeem A. Chaudhary, P.E. # 66470.

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INTRODUCTION

BACKGROUND

There is an increasing interest by public officials in the use of ramp metering for congestion mitigation at various freeway locations in the Dallas-Fort Worth (DFW) metroplex. DFW is currently in nonattainment for ground-level ozone, and transportation improvements in the area are subject to transportation conformity process. The Texas Department of Transportation (TxDOT) in collaboration with the North Central Texas Council of Governments (NCTCOG) initiated this project to assess if the use of ramp metering can improve operations of congested freeways, while improving air quality. Project objective was to identify at least two congested corridors and use computer simulation and modeling to evaluate impacts of ramp metering in these corridors. Initial corridor selection criteria included finding locations for which there is high level of confidence in overall success of ramp metering, and where no construction is planned in the near future. Assessment of potential diversion and adverse impacts on adjacent roadways was also of interest.

RAMP METERING

Overview of Objectives

Ramp meters—also called flow signals and ramp control signals—are traffic signals that control traffic at entrances to freeways (*1*). State departments of transportation (DOTs) install ramp meters to address three primary operational objectives:

- Control the number of vehicles permitted to enter the freeway.
- Reduce freeway demand.
- Break up platoons of vehicles released from an upstream traffic signal.

The purpose of the first and second objectives is to ensure that the total traffic entering a freeway section remains below the operational or bottleneck capacity of that section. A secondary objective of ramp metering is to introduce controlled delay (cost) to vehicles wishing to enter the freeway, and as a result, reduce the incentive to use the freeway for short trips during rush hour. However, there is a limit to the maximum delay drivers are willing to accept especially when convenient alternate routes do not exist. The purpose of the third objective is to provide a safe and efficient merge operation at the freeway entrance.

Most urban freeways are multilane facilities that carry heavy traffic during peak periods. However, traffic demand at a single on-ramp is usually a small component of the total freeway demand. Therefore, metering a single ramp or even few ramps may not be sufficient to achieve the first objective. In addition, drivers affected by a small ramp metering system perceive such a system to be unduly taxing them, favoring those who have entered the freeway at uncontrolled ramps at upstream freeway sections. Thus, ramp metering should be installed on a sufficiently wide section of a freeway if it is to achieve all its expected benefits and keep the motorists happy.

When properly installed, ramp metering has the potential to achieve the following benefits:

- Increased freeway productivity.
- Increased freeway speeds.
- Reduced trip travel time improved travel-time reliability.
- Safer operation on a freeway and its entrances.
- Decreased overall fuel consumption and vehicular emissions.

Ramp metering can provide significant benefits even if a subset of its objectives is satisfied. In this regard, the third objective is very important. Figure 1 illustrates the freeway breakdown phenomenon observed by Persaud et al. (*2*) many years ago.
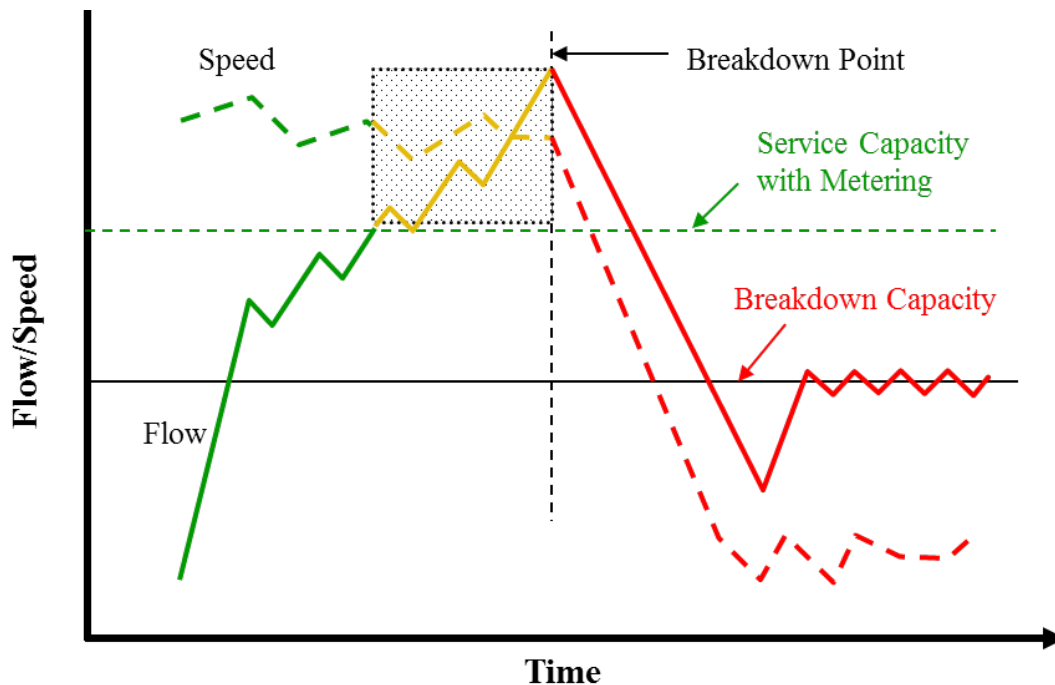
Figure 1. Freeway Breakdown Phenomenon.

The reader should note the following points:

- As traffic flow increases, average speeds may decrease but generally remain near free-flow speeds.
- For a short period just before breakdown, flow may be as high as 2600 vehicles per hour (vph). This region is marked by a shaded box.
- At breakdown, there is a drastic reduction in flow and speed. Vehicle speeds may even reach zero just upstream of the bottleneck. A queue condition forms.
- As the queue of vehicles discharges from the bottleneck, speeds start to increase and the freeway capacity stabilizes at the breakdown capacity level of 2100 to 2200 vph or even lower.

This two-capacity phenomenon often occurs at freeway entrance ramps where platoons of vehicles trying to enter the congested freeway create a bottleneck. The end-result is a reduction in service capacity. In addition, the shockwave created by a sudden drop in speed may travel for many miles upstream causing unsafe conditions. Ramp metering has the potential to minimize these effects by preventing freeway breakdown, thereby keeping freeway capacity at a significantly higher level as illustrated by the green dashed line. Even in cases where ramp metering is unable to prevent freeway breakdown, it has shown to delay its onset and reduce its duration.

Other researchers have also observed this phenomenon (*3*). Figure 2 shows a comparison of three-minute rolling average flow (green line) during freeway breakdown observed at a freeway facility in Australia in 2004 with flow on a rare day (red line) when breakdown did not occur. The area between the two lines highlights the capacity reduction due to freeway breakdown, which is quite significant.
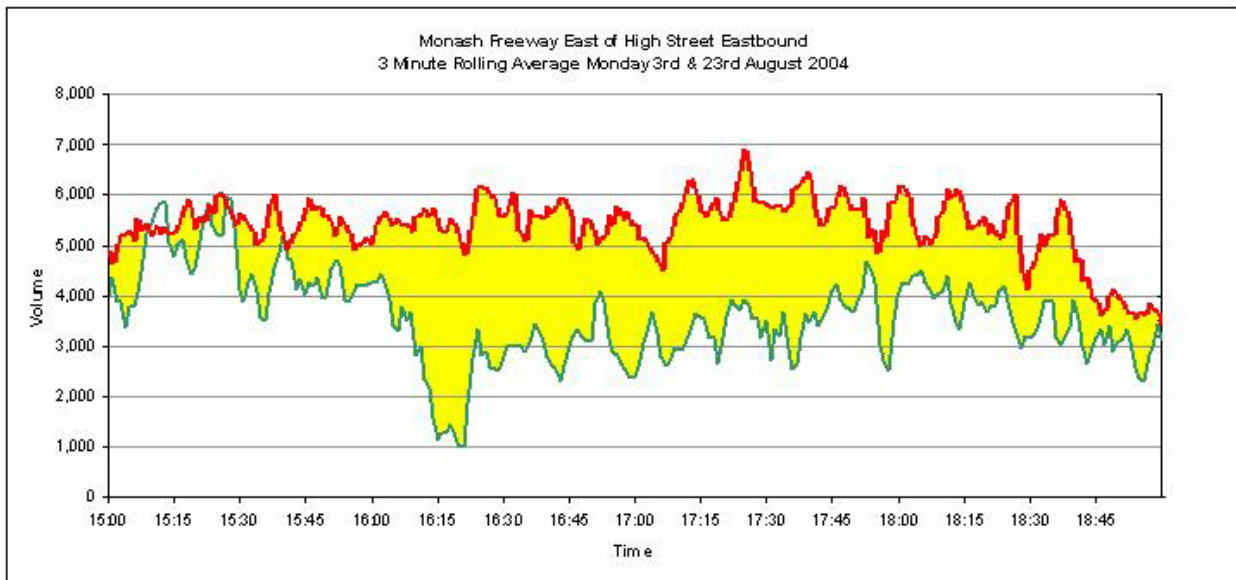
Figure 2. Observed Loss of Productivity at a Facility in Australia (*3*).

Ramp Metering Strategies

When the merge area of the freeway is not a bottleneck, an uncontrolled single-lane freeway entrance ramp can have a throughput capacity of 1800 to 2200 vph. The same ramp will have lower capacity when metered. The maximum theoretical metering capacity depends on the type of strategy used. There are three ramp metering signal control strategies. These signal control strategies are described in the following subsections.

Single-Lane One Car per Green

This strategy allows one car to enter the freeway during each signal cycle. Each signal cycle may have green, yellow, and red signal indications. The lengths of green plus yellow indications are set to ensure sufficient time for one vehicle to cross the stop line. The length of red interval

should be sufficient to ensure that the following vehicle completely stops before proceeding. From a theoretical point of view, the smallest possible cycle is 4 seconds with 1 second green, 1 second yellow, and 2 seconds red. This produces a meter capacity of 900 vph. However, field observations have shown that a 4-second cycle is too short to achieve the requirement that each vehicle must completely stop before proceeding. Also, any hesitation on the part of a passenger-car driver may cause the consumption of two cycles per vehicle. A more reasonable minimum cycle is around 4.5 seconds, obtained by increasing the red time to 2.5 seconds. This increase results in a meter capacity of 800 vph (per lane).

Single-Lane Multiple Cars per Green

This strategy, also known as platoon or bulk metering, permits two or more vehicles to enter the freeway during each green indication. The most common form of this strategy is to allow two cars per green. Three or more cars can be allowed; however, this will sacrifice the third objective (breaking up platoons). Chaudhary et al. (*1*) provide recommended signal interval durations and resulting meter capacities of two- and three- vehicle per cycle metering reproduced in Table 1. Contrary to what one might think, platoon metering does not produce a drastic increase in capacity over a single-lane one-car-per-green operation. The reason is that this strategy requires more green, yellow, and red times to ensure reliable operation as ramp speed increases, resulting in a longer cycle length. Consequently, there are fewer cycles in one hour.

Table 1. Meter Capacity for Bulk Metering.

Interval Times (sec)			
Interval	**Vehicles Per Cycle**		
	1	**2**	**3**
Red	2.00	2.00	2.32
Yellow	1.00	1.70	2.00
Green	1.00	3.37	5.47
Cycle Length	4.00	7.08	9.78
Meter Capacity	900	1017	1104

In cases where ramp demand includes a significant number of trucks or slow-moving vehicles, meter capacities may be lower than those provided in the above table. When implementing platoon metering, a specific regulatory sign message can also be displayed to denote the desired (maximum) number of vehicles entering per green (signal cycle per lane), such as TWO CARS PER GREEN. Displaying this message requires predetermination of the number of cars to allow per cycle.

Multilane Metering

Meter capacity can be significantly increased by using multilane metering, where a ramp is widened to provide multiple lanes and vehicles from each lane take turns entering the freeway. The most common form of this strategy is dual-lane metering, which requires two lanes on a ramp in the vicinity of the meter. In this strategy, the controller operates by alternating the green-

yellow-red cycle for each metered lane. Depending on the controller being used, the cycle may or may not be synchronized. The ramp controller used in Texas provides a synchronized cycle where the green indication never occurs simultaneously in both lanes. The green indications are timed to allow a constant headway between vehicles from both lanes. Dual-lane metering can provide a metering capacity of 1600 to 1700 vph, approaching the geometric related capacity of the ramp. In addition, dual-lane ramps provide more storage space for queued vehicles.

A form of dual-lane metering is a case where the second lane is reserved for high occupancy vehicles (HOVs). In this strategy, HOVs get priority over non-HOVs. The HOV lane may or may not be metered. Metering with HOV priority lane encourages carpooling, with the intent of reducing vehicle demand.

Types of Ramp Metering

Practitioners and researchers classify ramp metering according to several categories. The following description of these classifications is adopted from Chapter 7 of the Freeway Management and Operations Handbook (*4*).

Local versus Systemwide

Local metering uses local traffic conditions to select metering rates. Systemwide metering establishes metering rates for several ramps based on traffic conditions for the entire freeway segment containing the selected ramps.

Pretimed versus Traffic Responsive

Pretimed systems use metering rates established using historical data. These rates are preprogrammed in the ramp controller and activated by a time-of-day schedule. Pretimed systems cannot respond to fluctuations in traffic conditions. Traffic responsive strategies use data from freeway detectors to activate metering and select (or compute) metering rates as freeway conditions change. Traffic responsive metering may also adjust metering rates based on ramp demand.

Restrictive and Non-Restrictive Metering

A restrictive or strict metering strategy sets metering rates below the non-metered demand level. This type of metering achieves the maximum benefit to freeway traffic but often results in ramp queue reaching the upstream intersection and blocking it. A non-restrictive strategy sets the metering rate equal to the average non-metered ramp demand.

Metering with Queue Override

Queue override can be used with any type of metering. In the less restrictive operation, a queue condition on the on-ramp forces the implementation of maximum metering rate. In the more restrictive case, a queue condition on the on-ramp shuts the metering operation off until the queue has dissipated. Texas uses this type of operation. The latter case requires that sufficient storage space (distance from stop bar to queue detector) be provided to contain the cyclic arrival of a platoon of vehicles from the upstream signal.

Integrated Operation of Ramp and Upstream Traffic Signal

In certain situations, it may be possible to improve ramp metering operation by controlling or metering ramp demand at approaches to the upstream signal. In this approach, the objective is to distribute excess ramp demand before it reaches the on-ramp.

WORK PERFORMED

To achieve project objectives, researchers:

1. Conducted a state of practice review and evaluated the utility of existing data.
2. Using existing speed data, identified severity and duration of congestion in several freeway corridors.
3. Used a dynamic traffic assignment (DTA) model to study impacts of ramp metering in selected corridors and up to 5-mile beyond.
4. Conducted microsimulation-based analysis to study impacts of ramp metering on the corridor and immediate vicinity in more details.
5. Developed DFW-specific emissions rates from the MOVES model and applied these rates to simulation outputs to assess air quality impacts of ramp metering.
6. Estimated potential costs and benefit of ramp metering.
7. Developed recommendations and guidelines.

The remainder of this report provides details of work performed and findings.

STATUS OF RAMP METERING IN TEXAS

OVERVIEW

TxDOT initially used ramp meters from late 1960s through early 1980s (*5*, *6*), but removed these meters, located along I-10 in Houston and I-35 in Austin, upon reconstructing these freeways facilities. With the increase in freeway congestion along Houston freeways in the 1990s, TxDOT Houston District's (HOU's) interest in the use of ramp metering reemerged. By early 2000, Houston had 159 ramp meters installed along various segments of I-10, I-45, I-610, US 290, and SH 1225 (*7*). One of these meters provided dual-lane metering, one used bulk metering, and all the remaining meters were single-lane meters using one-care-per green strategy. Factors key to the initial success of ramp metering during this round of implementations were:

- Full staff support at levels within the district, including District Engineer, middle management, and field technicians.
- District's policy, implemented with the use of queue flush mode, to keep maximum delay to on-ramp vehicles below two minutes.
- An extensive media campaign entitled "Go with the Flow" (*8*), to rally public and partner-agency support.
- Commitment to use district funds for operations, maintenance, and short-term field studies to evaluate and refine operations of ramp meters.

Over the years, TxDOT also funded numerous research and implementation studies/projects to address identified needs. One such implementation project facilitated the installation of a five-ramp metering system along SH 360 in Arlington, Texas (*9*). This system, located immediately north of the I-20 interchange, became operational in June 1999 after an extensive media campaign. However, several issues resulted in the eventual removal of this system. These issues included:

- Peak-hour traffic demand at the last ramp in the system was higher than the capacity of a single-lane ramp meter. Furthermore, any diversion of ramp traffic was not possible due non-existence of frontage road in this section of freeway. As a result, the meter was mostly in a flush mode during the peak hour and ineffective.
- The system was not large enough to be able to counter the impacts of significant uncontrolled demand from I-20 to SH 360 freeway-to-freeway ramps.
- The district did not make available additional resources (funding, staffing, etc.) for day-to-day system operations and maintenance. Thus, staff on the ground was not happy about addition to their responsibilities.

HOU is the only TxDOT jurisdiction that has continued to operate ramp meters, although there are far fewer metered ramps than early 2000s. Reconstruction of freeways since then (for instance I-10) has resulted in the removal of more than half of the meters that existed during that time. However, metering has continued to be a part of TxDOT congestion management strategy. In addition, HOU has been instrumental in pushing several research projects through the TxDOT's traditional research program. The following sections describe these initiatives.

RAMP METER DESIGN CRITERIA

In late 1999, TxDOT initiated research project 0-2121 to develop design criteria for ramp metering (*10*). This research outlined three key design factors for safe and efficient operation of ramp meters. The following subsections summarize key design factors.

Acceleration Distance

This criterion recommends desired meter-to-merge acceleration distance for vehicles forced to stop at the meter to accelerate and reach safe freeway merge speeds. Figure 3, reproduced from the above reference, provides curves that can be used to select recommended acceleration distance for three grades.
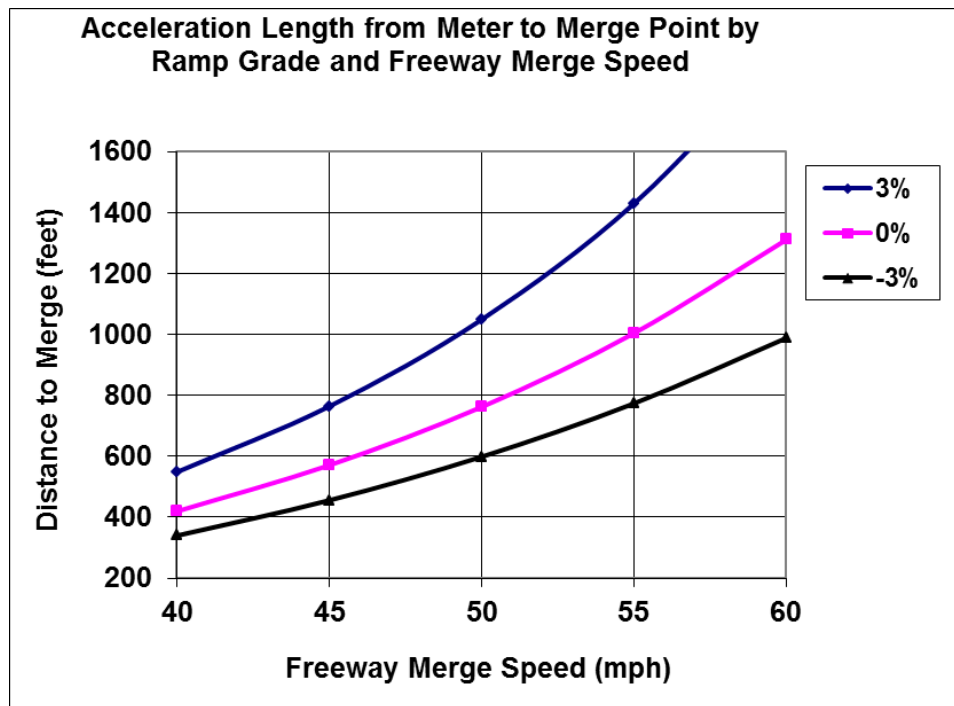
Figure 3. Meter-to-Merge Acceleration Distance Criteria.

Queue Storage Distance

This is the distance upstream of the stop bar (meter) to store platoon of vehicles from upstream signal, arriving at a higher hourly rate than the average ramp-demand (flow) rate. Generally, this is the distance between queue detector and stop bar. The following equation provides the relationship between recommended storage distance (L) as a function of ramp volume (V):

$$L = 0.82V - 0.0002435V^2, \ V \leq 1600 \text{ vph}$$

Stopping Sight Distance

A minimum stopping sight distance of 250 ft downstream of upstream signalized intersection was recommended to allow approaching vehicles to safely stop before reaching the maximum queue.

TxDOT research project 0-2121 also produced a document containing a condensed version of geometric design criteria and signal placement guidelines (*11*) that could be readily added to the existing roadway design manual.

Performance Measurement

Research project 0-2121 also developed a performance measure called metering availability, which is the percent of time a meter is actually metering. It is calculated as:

*[Metering duration (MD)-flushing time]/MD*100*

Figure 4 provides a graph of metering availability for several ramp-metering strategies. It also qualitatively categorizes metering quality in terms of the good, fair, and fail for different demand levels.
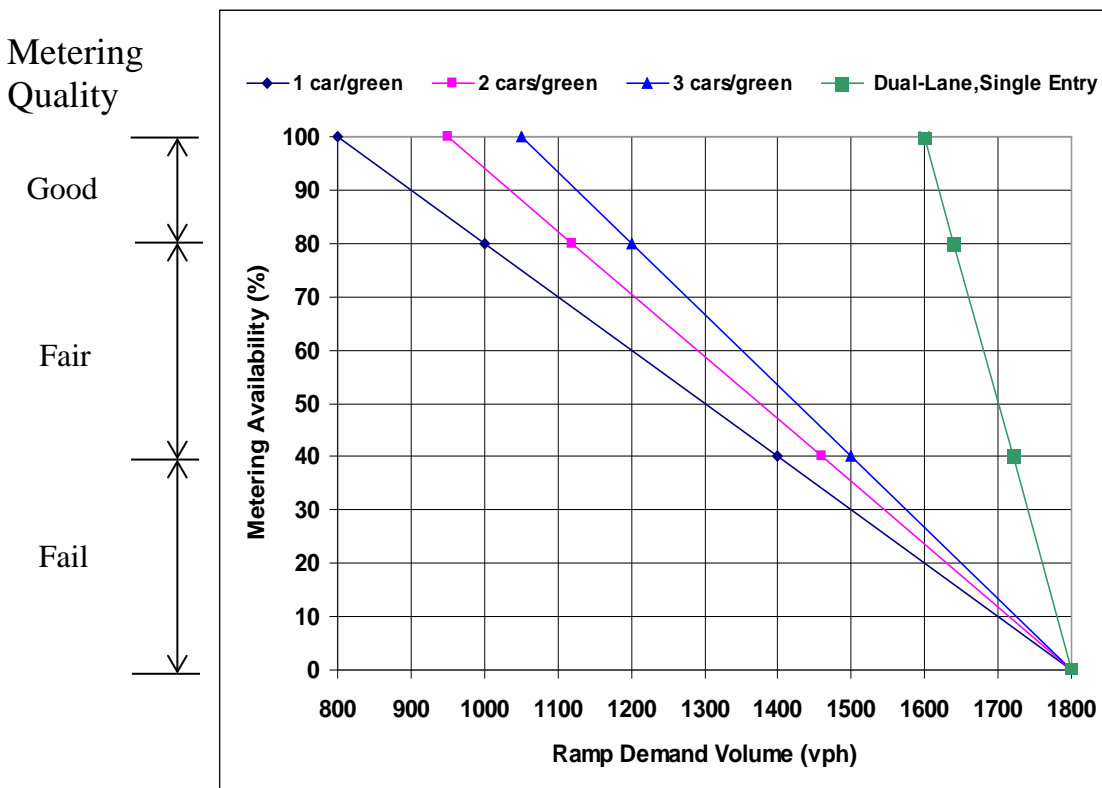
Figure 4. Metering Quality for Various Ramp Metering Strategies.

A later TxDOT research project used computer simulation to study the effectiveness of metering with queue flush operation (*1*). This research found that frequent queue flushing can be

counterproductive and recommended that meter availability should be 90 percent or higher for a ramp meter to be effective. A key to achieving this objective is to provide sufficient storage for cyclic peak demand. In addition, overall ramp demand should be lower than meter capacity. This reference also provides details about the various components of ramp meters in Texas, including sensors and regulatory signs. Appendix A reproduces this information.

RAMP METERING INSTALLATION WARRANTS

In 2006, TxDOT initiated another research project to develop ramp-metering warrants. Building on previous TxDOT-sponsored research, guidelines and practices in other states, and controlled computer simulation studies, researchers developed criteria and guidelines for installing, operating, and removing ramp meters (*12*). Topics addressed in this project included:

- Approval process, including an authorization form.
- Installation criteria, which include consideration of ramp and freeway traffic and safety considerations. Factors such as diversion, equity, potential impacts on air quality, and public perception are also discussed.
- Operational considerations, including hours of operations, establishing metering rates, traffic responsive operation, queue management, and startup and shutdown procedures.
- Removal of ramp meter, including a removal authorization form.
- Special operations, including HOV bypass lanes and operation during incidents.
- Monitoring and performance measurement. Performance measures include: average meter start and end times, average number of activations, average active duration, average wait time, average freeway speed, average number of flushes, flush frequency, mean flush duration, and meter availability.
- Enforcement, including strategies and provision of enforcement area.
- Maintenance, including responsive and preventative.

Appendix B reproduces traffic and design criteria developed in this project to provide for easy referencing.

STATUS OF RAMP METERING OPERATION IN HOUSTON

TxDOT currently uses traffic responsive mode, which activates all ramp meters based on freeway traffic conditions. Most of these meters operate as isolated signals, with no center-to-field communication. Lack of center-to-field communications is primarily due to limitations of the now outdated ramp controllers. During the past decade, TxDOT has removed a significant number of ramp meters due to reconstruction project to widen freeway facilities. Currently, there are only 60 ramp meters, located along I-45, I-610, and US 59. Figure 5 shows the locations of these meters.

In 2016, HOU funded an inter-agency study to evaluate if the need for a subset of ramp meters still exists (*13*). This study examined a subset of 10 on-ramp located along US 59 (Future I-69). Figure 5 highlights this set of ramps.
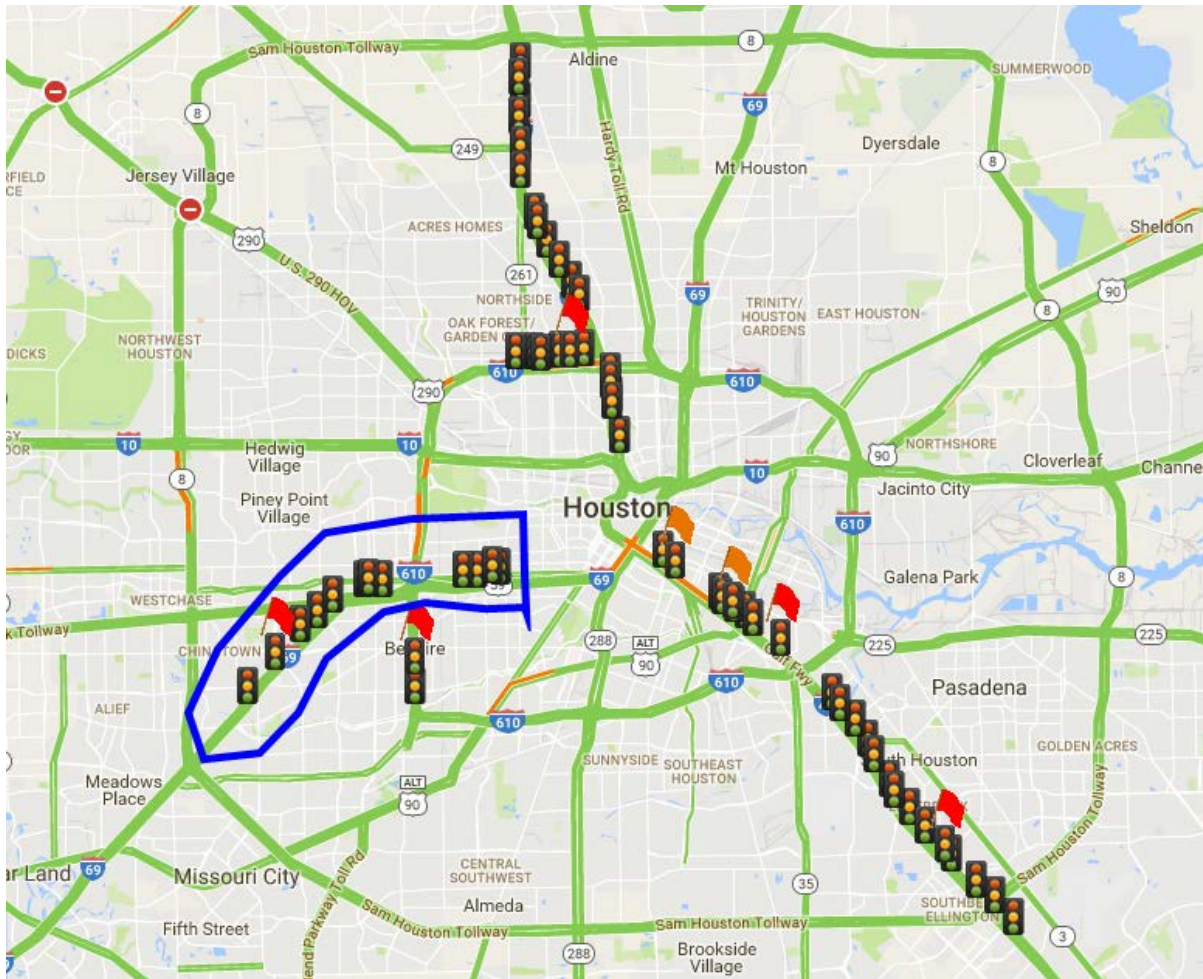
Figure 5. Locations of Ramp Meters in Houston (Source: TranStar).

The 2016 study collected traffic and crash data and applied the criteria developed by Balke et al. (*12*) and reproduced in Appendix B. This study concluded that eight of these 10 ramps still meet ramp installation criteria. The study also evaluated current operational and maintenance logs for an 18-month period from January 1, 2015, to June 30, 2016, for all ramp meters in the district. This study identified 239 records showing problems with equipment. Of these, 73 cases related to signal pole knockdown and 14 cases of loop/communication failure. According to HOU, maintenance cost of ramp metering in Houston is $16,000 per month. The study recommends improved data collection to identify the causes of signal-knockdown incidents so that strategies could be implemented to prevent these incidents.

From the beginning, HOU has used an off-the-shelf controller, built to TxDOT specifications, to provide ramp metering. The plant that manufactured these controllers closed several years ago. Therefore, TxDOT is currently evaluating another controller option to replace controllers at all locations. This change will also require replacement of all existing controller cabinets. Replacement of old field hardware will also enable TxDOT to provide center-to-field communications using existing fiber- or copper-based communications infrastructure. This change will also provide TxDOT means to implement system-based control of selected group of

ramp meters. HOU is currently conducting a demonstration project, which has already installed new controllers at six ramps along I-45. Five of these locations use old cabinets and one location uses a new cabinet. At these sites, TxDOT has also switched from inductive loops to radar sensor for the detection of freeway conditions for traffic responsive operations. With this change in hardware, TxDOT has also switched from the use of mainline occupancy to mainline speed for activating metering operations. TxDOT is currently investigating the roles of central software and peer-to-peer communications for providing system-based control of multiple ramp meters and their potential coordination with controllers at adjacent signalized interchanges to provide a dynamic system.

STATUS OF RAMP METERING IN THE UNITED STATES

OVERVIEW

The Federal Highway Administration (FHWA) primer on ramp metering identifies over 20 states with ramp metering systems (*14*). Figure 6, reproduced from this source, graphically shows the locations and extent of metering in the country. Two California regions and Minneapolis have more than 300 ramps.

Figure 6. Status of Ramp Metering in the United States (*14*).

FHWA ramp metering primer also provides the following ranges of key benefits reported by various jurisdictions:

- Travel speed increase: 5 percent to 165 percent reported.
- Travel time reduction: 20 percent to 160 percent.
- Collision reduction: 10 percent to 40 percent.
- Benefit cost ratio: 15 to 1.

Denver and Minneapolis also report emissions reduction of 20 percent and 50 percent, respectively.

Based on a survey of states, the FHWA Primer also identifies key barriers to ramp metering and offers mitigations strategies. Table 2 lists these barriers and corresponding mitigations strategies.

Table 2. Barriers and Challenges to Ramp Metering.

Barrier	Response	Mitigation Strategy
Existing Ramp Geometry	58%	Conduct feasibility studies, implement alternate metering strategy, develop plan to improve geometry
Cost/Funding	42%	Conduct cost/benefit and feasibility studies
Public Opposition	33%	Conduct public outreach
Heavy Ramp Volume	25%	Implement queue management strategies
Local Agency Opposition	17%	Share results of cost/benefit analysis, measure and share performance metrics
Lack of Agency Support	17%	Communicate internally often and clearly during planning phase, sow/illustrate benefits, and cost effectiveness of strategy

The FHWA *Freeway Management and Operations Handbook* (*15*) identifies ramp metering as a key ramp management strategy, together with ramp closure, special-use treatments (i.e., HOV bypass lanes), and ramp terminal treatments (i.e., signal timing adjustments). The report states that:

- When properly planned and implemented, ramp management can be an important element of a freeway management program.
- Ramp management strategies are not appropriate for all situations.
- Ramp metering implementation does not eliminate the need to pursue other complimentary strategies.
- The potential use of ramp management strategies should be examined thoroughly before any such improvements are made. A comprehensive approach in planning, designing, implementing, and operating ramp metering can help ensure success.

According to this report, ramp-metering implementation is a process that begins well before actual implementation and requires equipment purchase, coordination internally to make sure there is support, examination of minimum requirements, identification of ramp control strategies, staffing levels and needs assessment, assessment of hardware and software needs, and staff training. It also emphasizes the need for public outreach to build consensus. Such outreach includes informational meetings and media campaigns targeted to local leaders and motorists. The report also identifies other elements of successful implementation, which include development of agency agreements, policies, and procedures for both intra- and inter-agency cooperation and policies governing maintenance, including:

- Replacing defective or broken components.
- Updating software and system inventories.
- Logging repairs.
- Testing equipment.
- Cleaning system components.

These activities require availability of trained staff and funding. Performance monitoring is also necessary to determine if intended objectives are being achieved. Performance measures identified in this document include: throughput, travel time, travel-time reliability, benefit cost analysis, and public perception and acceptance.

The following subsections provide more detailed information about status of ramp metering in various states and other information about their practices.

ARIZONA DOT

Arizona DOT's (ADOT's) ramp metering design guide (*16*) provides warrants and geometric requirements for ramp metering. This document also provides details about required hardware, including locations and specifications of sensors, pavement markings, and signs. Additionally, a 2013 study conducted by Simpson et al. (*17*) provides operational guidelines. Below is a summary of key points from these documents:

- Objectives of ramp metering:
    - Minimize trip travel time.
    - Minimize fuel and emissions.
    - Minimize crashes.
    - Avoid spillback.
- Ramp warrants:
    - Ramp volume is at least 400 vph.
    - Ramp plus outside-freeway-lane volume is at least 2050 vph.
    - General purpose lane speeds are less than 50 mph during recurring congestion adjacent to the ramp or up to 2 miles downstream for the same data collection period.
    - A minimum of 400 ft storage distance should be available upstream of the meter signal.
    - Sufficient acceleration distance should be available for vehicles to reach safe merge speeds.
- Desired data:
    - Data used for designing new ramp should be less than 1 year old, but up to 3-year data old could be used upon ADOT approval. Use 20-year projections.
    - For ramp metering analysis, use 72 hours of 5-minute data collected during typical Tuesday through Thursday.
- Other considerations:
    - Is it safe to install ramp meter?
    - Is power source reasonable obtainable?
    - Is there access for maintenance?
    - Is it desirable to distribute demand to other ramps?
    - Are recommendations easy to implement?

ADOT operational guidelines recommend simple formulae for calculating fuel consumption and emissions. Fuel consumption (gallons) is calculated as a function of distance traveled, delay, and stops. The recommended calculation method uses multiplications factor (of 69.9, 13.6, and 16.2) to estimate amounts of carbon monoxide (CO), oxides of nitrogen (NOx), and volatile organic compounds (VOC) from estimated fuel consumption.

ADOT does not use freeway-to-freeway metering. As of December 2013, ADOT had 39 single-lane and 162 dual-lane meters, all activated during AM- and PM-peak periods via time-of-day schedule. When activated, ramp meters operate under local traffic-responsive mode with six recommended metering levels, where Level 1 provides the fastest metering. ADOT programs controllers to switch between these levels based on occupancy data from demand and queue detectors. Queue detector occupancy of 50 percent triggers a queue condition and a value of 10 percent cancels queue condition.

CALTRANS

As part of their congestion-management and protection-of-highway-investment strategy, Caltrans has been committed to ramp metering since 1960 (*18*). The specific goal of ramp metering is to reduce freeway traffic congestion and travel time. As of November 2017, there were 3,014 ramp meters across nine out of 12 Caltrans districts. Most of these meters use local traffic-responsive metering rates based on freeway conditions. Past studies have shown a wide range of benefits from these meters in different corridors, including a 30–55 mph increase in speed and 30 percent reductions in travel times and delays. Caltrans ramp metering development plan, updated on a regular basis, uses data from districts provides average conceptual construction cost for constructing ramp meter. Table 3 provides latest published estimated cost of single and dual-lane ramp meters. According to information provided by Caltrans staff in October 2018, ramp meter installation across the state ranges from $125k to $155k and typical operations and maintenance (O&M) costs for ramp meter are approximately $6k per year.

According to the 2014 Annual Report (*19*), Caltrans District 7 alone had 999 ramp meters, including many on freeway-to-freeway ramps. According to this report, in 2014 Ramp Metering Branch staff performed 1561 field inspections, reported 656 issues to ITS and Electrical branches, responded to 173 complaints and inquiries, and 173 ramp metering parameter adjustments. Other ramp metering-related tasks include 55 traffic data collections, 208 project reviews, 501 meetings, and 26 ramp metering related studies. The number of tasks performed in each category varies from year-to-year.

Table 3. Caltrans Conceptual Construction Cost Estimates of Ramp Meters.

No. of Lanes	Electrical Cost ($K)	Civil Cost ($K)	Total Cost ($K)
1-Lane	140	250	380
2-Lane	160	740	900
Notes:			

Notes:
1. Electrical Costs include signals, conduit, controller, cabinet, advance warning signs and signal, mainline, and on-ramp detection.
2. Civil Cost includes civil work to widen the on-ramp, maintenance vehicle pullout (MVP), enforcement area, signing, and striping.
3. Cost estimates for an average length ramp and may vary for shorter or longer ramps.
4. Costs do not include structure work or right of way acquisition costs.
5. These estimates do not include additional cost of support and contingencies, estimated to be 33% and 25% of the above costs.

Below is a description of functions performed by different branches within Caltrans:

- Ramp Metering Branch performs periodic field surveillance and corrects software and hardware issues associated with ramp metering. Staff from this branch is also responsible for proper operation of ramp meters district wide and provide support to Area Engineers, who are responsible for routes or subroutes assigned to them.
- Electrical Maintenance Branch is responsible for initial meter timing and operation, and responds to ramp meter malfunctions by California Highway Patrol and from other Caltrans branches thereafter. In addition, staff from this branch is responsible for checking/inspecting each meter every 120 days. This work includes:
  - Field inspections of hardware that include signal indications and their alignment, other hardware (signs, posts, back plates, etc.), pull boxes to ensure covers are present, and clear of dirt.
  - Cabinet interior inspection including controller indications, functions/timing, detector indications, outputs. Cabinet interior is cleaned as necessary.
  - Cabinet exterior to ensure cabinets are clean, locks and handles are in good condition, and police panel switches are working properly.
- ITS Branch is responsible for technical support to the Traffic Management Center (TMC), developing and testing new metering software, configuration of ATMS and related reporting, and maintaining TMC to field communications.

Caltrans ramp metering design manual (*20*) contains details of requirements related to geometric design, hardware and system integration, signing, and pavement markings. Key points to note are as follows:

- Accommodations for metered HOV lanes must be provided at all metered ramps.
- Minimum storage length (general or HOV) is equal to 7 percent of peak demand multiplied by 29 ft/vehicle).
- Deceleration distance is equal to stopping sight distance.
- Stop line must be placed 75 ft upstream of the 23-ft separation line (right edge of freeway travel lane to left edge of merge lane).
- Exit ramps shall have a detector located at 23-ft separation point.

GEORGIA

According to the Georgia Department of Transportation's (GDOT's) 511 webpage (*21*), there are over 160 ramp meters in and around Atlanta. These meters operate during specified peak periods and activate based on traffic conditions. According to draft ITS design manual (*22*), GDOT's policy is to consider metering at all surface-street to freeway entrance ramps in the Atlanta Metro areas. The manual provides the following interim guidelines when considering ramp meters:

- Install ramp meter if peak-hour ramp volume is greater than 240 vph and either:
  - Freeway volume-to-capacity ratio is more than 0.88, or
  - Collision rate is greater than 2 per million vehicles.
- Ramp meter is not essential under other conditions but may be installed for other reasons.

The guidelines provide three criteria for the placement of stop bar. These are:

- Providing a safe acceleration distance between the stop bar and the point where vehicles will be required to merge with mainline traffic.
- Placing the stop bar upstream of the physical gore to discourage drivers from leaving the ramp meter queue and entering mainline traffic.
- Preserving the longest possible storage length on the ramp.

The document also provides a table of recommended minimum acceleration lengths for various design speeds. Table 4 reproduces these data.

Table 4. GDOT Recommended Minimum Acceleration Length for Metered Ramps.

Design Speed (mph)	Speed Reached (mph)	Distance Required from STOP condition (ft)
50	39	720
55	43	960
60	47	1,200
65	50	1,410
70	53	1,620
Source: A Policy on Geometric Design of Highways and Streets, (Green Book), AASHTO, 2004, exhibit 10-70		

The minimum acceleration distance is measured from the farthest point a merging vehicle can travel down the entrance ramp and acceleration lane before it must merge with mainline vehicles. The recommended final merge point is where the width of the acceleration lane drops below 12 ft. The manual recommends using some other point as the basis for measuring the acceleration distance in the case of added lane.

Other recommended field considerations include:

- Consider restriping ramp to increase storage space.
- If ramp is wide enough, consider providing two metered lanes.
- Preserve 10-ft outside shoulder and 4-ft inside shoulder (especially if a guardrail or barrier is not present), to accommodate disabled vehicles.
- Consider impact on trucks where truck volume is high.
- Signals for single-lane ramps
  - Use pole-mounted signals with 12-in. displays facing approaching traffic and 8-in. displays facing waiting vehicles.
  - Pole should be mounted on a breakaway base and installed 6 ft downstream of stop bar and 8 ft away from the travel lane.
- Signals for multilane meters.
  - User two 3-section signals per lane, with a vertical clearance of between 17 and 19 ft.
  - Place the mast arm 60 ft downstream of stop bar.

- Sensors:
  - In each metered lane, place presence detector (a 6×40 loop) 4 ft upstream of the stop bar.
  - In each metered lane, place a passage detector (a 6×6 loop) 4 ft downstream of the stop bar.
  - Place queue detectors (a 6×6 loop) at 80 percent distance from stop bar to upstream intersection.
- Place advance warning flasher next to queue loop.
- A CCTV camera is required for ramp metering operations. It is desirable to see the entire ramp, but the ability to view the meter is critical.

KANSAS

In 2010, Kansas City Scout program installed a small pilot ramp metering system along I-435, with the goal of improving traffic operation and improving safety (*23*). The system has seven ramp meters. Kansas DOT and Missouri DOT jointly manage this system. An evaluation study conducted 12 months after installation concluded that ramp metering effectively improved I-435 by:

- Decreasing overall accidents on the freeway by 64 percent.
- Cutting merge-related crashes by 81 percent.
- Making merging easier at a more consistent rate within the corridor.
- Sustaining overall travel times and speeds at reliable levels, despite increased traffic volumes.

As part of the pilot program, Scout also conducted an outreach campaign to educated motorists, emergency responders, and law enforcements personnel. Two thirds of residents responding to a 2011 survey indicate that the meters have improved the freeway operations.

Researchers obtained the following additional information about experiences from Kansas City agency staff via telephone:

- All ramp meter signals in the pilot system were retrofit. No geometric changes were made to optimize storage or acceleration distance. As a result, many meters were flushing too much and they had to change the operation from one-car per green to two-cars per green.
- Meters start with a lower metering rate, which quickly changes to maximum metering rate.
- Cost of initial installation was $125K, which included:
  - New cabinet installation.
  - Pedestal-mounted signal heads (one on left side for single lane and two for multilane ramps), flashing beacons, sensors, striping, and static signs.
- Radar sensor costs an additional $10K.
- Maintenance issues encountered:
  - #1 traffic hitting flashing beacon.
  - #2 traffic hitting signal head.

- o Traffic knocking static signs.
- Maintenance:
  - o Cost of $15K/ramp/year.
  - o DOT staff performs routing maintenance twice a year.
  - o Other labor is outsourced.
  - o Above cost does not include cost of Traffic Engineering side. This cost is unknown.

LOUISIANA

In June 2010, Louisiana Department of Transportation and Development (DOTD) began stage-wise installation of 16 ramp meters along the I-12 corridor from Baton Rouge to Livingston Parish. All 16 of the ramp meters were fully functional in summer 2012 (*24*). The objective was to protect state's investment on the Geaux Wider Program (a public awareness campaign in association with I-12 widening project), improve travel times, and increase safety by reducing the potential for vehicle crashes at merge points. The ramp meters operate exclusively during peak travel times, which are 6–9 a.m. for westbound (WB) on-ramps and 3–7 p.m. for eastbound (EB) on-ramps, and during special events or incidents. Prior to ramp metering implementation, DOTD developed an outreach plan and folded it into the Geaux Wilder Program (*25*). Specifically, DOTD added ramp metering information to the program webpage and mailing list, conducted public meetings to educate people about the benefits of ramp metering, and broadcasted DOTD staff and guest interviews on several newscasts and radio stations. Two key points communicated to public were:

- Staff will monitor ramp meter operation from the Traffic Management Center located at DOTD headquarters.
- Ramp metering will include a flush function to prevent any ramp queues from reaching side streets.

DOTD commissioned an evaluation study to evaluate the safety and operational benefits of the ramp metering system (*25*). Below is a summary of findings from this study, which compared before and after travel time, ramp delay, and per year crashes for periods between 2005–2008 (pre-ramp metering) and 2010–2011 (post-ramp-metering):

- Peak-hour volumes remained unchanged after ramp metering.
- Crashes:
  - o WB crashes during morning peak period (AM) reduced by 17 percent.
  - o EB crashes during evening peak period (PM) reduced by 7 percent.
  - o At one location, crashes attributed to ramp merge operation reduced from 21 to 6.
- Mainline travel times:
  - o AM WB travel time reduced by 15 percent.
  - o PM EB travel time reduced by 19 percent.
- Vehicular travel time increases for cross street traffic ranged from 7 seconds to 85 seconds for metered ramps. However, the average freeway travel-time savings of over four minutes more than compensates for this delay.
- Flush operation:
  - o At one location (O'Neal Lane), heavy AM ramp demand caused the meter to consistently flush and hamper any benefits of metering, particularly due to large

platoons created by metering. At this location, ramp metering made the situation even worse due to construction on a parallel surface street route. At this location, the long-term solution is to add a metered lane.
- o At another location (Millerville Road) with a loop ramp, high volume together with insufficient storage space caused the meter to flush throughout the morning commute. This study also observed that flushing of large platoons causes unwanted freeway congestion and potential safety issues.
- Metering times:
  - o WB ramp meters currently operate from 6:00 a.m. to 10:00 a.m. This study recommended changing the ramp metering operation duration from 6:15 a.m. to 9:00 a.m.
  - o For the EB direction, the study recommended changing the start time of metering operation from 2:00 p.m. to 3:00 p.m.
- Benefit and cost of ramp metering:
  - o Study used $16.01 and $105.67 as the per hour cost of delay to passenger cars and trucks, respectively.
  - o Ramp meters saved 131,625 hours of lost time per year, an equivalent of $3,287,466 of savings per year.
  - o Installation of 14 ramp meters present at the time of this study was $1,200,000 ($85,714/meter).

MINNESOTA

Minnesota DOT (MnDOT) started installing ramp meters in 1969 and by 2002 had 430 ramps meters to manage freeway access on approximately 210 miles of freeways in the Twin Cities metropolitan area (*26*). All these meters operated using a strict-metering strategy, disliked by the motoring public. In 2000, a bill passed by the Minnesota Legislature required MnDOT to evaluate the effectiveness of ramp meters in the Twin Cities Region by turning off all meters. Turning off ramp meters resulted in the following negative impacts (*26*):

- A 9 percent reduction in freeway volume.
- A 22 percent increase in freeway travel times.
- A 7 percent reduction in freeway speeds, which contributed to the negative effect on freeway travel times. Freeway travel-time reliability declined by 91 percent.
- A 26 percent increase in crashes. These crashes broke down to a 14.6 percent increase in rear-end crashes, a 200 percent increase in side-swipe crashes, a 60 percent increase in run off the road crashes, and an 8.6 percent increase in other types of crashes.

Additionally, this study showed that ramp metering produced a yearly reduction of 1,160 tons of emissions. The study also showed net yearly benefit of $32 million resulting from ramp metering. Market research data collected as part of the evaluation project showed a significant change in public attitude after MnDOT shut off the meter, including:

- Most survey respondents believed that traffic conditions worsened.
- Support for metering system increased, but most respondents demanded changes such as use of faster cycle times, shorter operating hours, and fewer meters.

In 2002, MnDOT launched its new responsive ramp meter system with the following policies:

- Ramp meter waits will be no more than four minutes on local ramps and no more than two minutes on freeway-to-freeway ramps.
- Vehicles waiting at meters will not back up onto adjacent roadways.
- Meter operation will respond to congestion and only operate when needed.

MnDOT uses the following ramp metering warrants (*27*):

- Corridor-wide deployment (typically a 3–6-mile segments called a zone) is warranted if:
  - During peak period, the zone under consideration has a 30-minute period where:
    - The demand (measured in 5-minute intervals) exceeds 95 percent of downstream capacity, or
    - 30-second flow rate at all ramps in the zone exceeds 100 vph.
  - Within 500 ft in either direction of ramp gore, crashes exceed typical crash rate.
  - Hourly ramp per lane ramp volumes are in the 240–900 range.
- Isolated ramp meter deployment:
  - Freeway:
    - Operates below 50 mph for at least 30 minutes for 200 or more days in a calendar year, or
    - Has high frequency of merge-related crashes, or
    - Ramp meter will result in an increase in high occupancy via preferential treatment of HOVs, or
    - Ramp meter will contribute to balancing demand and capacity at a system of adjacent ramps, or
    - Ramp meter will mitigate predictable sporadic congestion on isolated sections of freeway due to special events.
  - Total mainline plus ramp demand exceeds:
    - 2,650 vph for a two-lane freeway, or
    - 4,250 vph for a three-lane freeway.

MnDOT algorithm attempts to keep traffic exiting from each zone below downstream capacity by monitoring and controlling traffic entering and existing that zone. Thus, it requires sensors at all exit ramps. This algorithm distributes excess demand to all on-ramps in the zone. In doing so, it maintains the minimum metering rate constraint at each ramp.

According to information provided by MnDOT staff, it costs $10 to $15k to install a new ramp meter. This cost includes signal heads and poles, signal cabinet and controller and on-ramp detection. Average yearly maintenance cost per meter is around $2,500, the bulk of which is to replace/repair knocked down signal poles.

NEVADA

Nevada DOT (NDOT) uses ramp metering in Las Vegas and Reno areas along major interstates and freeways (*28*). NDOT has a *Managed Lanes and Ramp Metering Manual*. Part 1 of this document contains policies to guide deployment of management lanes and ramp metering (*29*). The document identifies NDOT as the primary responsibility to coordinate changes related to

agencies and jurisdictions affected by the change. This policy document specifies the following goals of ramp metering:

- Improve safety, travel speed, freeway throughput.
- Manage ramp delay and excessive queues.
- Avoid cut through traffic in neighborhoods.
- Promote car-pooling and bus use.

Furthermore, this document outlines policies related to operation (i.e., hours of operation, data-to-day activities), maintenance, enforcement, initial operations, performance measurement (monitoring, analysis, and reporting), public information and outreach, funding, staffing (skills and training), and software.

Part 2 of this manual provides ramp-metering warrants (*30*). Table 5 lists these warrants.

Table 5. NDOT Ramp Meter Warrants.

Number	Name	Description
1	Ramp Volume	Is the peak-period ramp greater than practical lower limit of 240 vph/l?
2	Safety	Is the rate of crashes within 500 ft in either direction of the gore point greater than the mean crash rate for comparable freeway sections?
3	Speed	Does the freeway operate at speeds less than 50 mph for duration of at least 30 minutes for 200 or more calendar days per year?
4	Level of Service	Does the freeway operate at LOS D or worse during the peak period?
5	Volume 1	Does the total volume downstream of the gore during the peak period exceed the following? ♦ Two mainline lanes in one direction – 2,650 vph ♦ Three mainline lanes in one direction – 4,250 vph ♦ Four mainline lanes in one direction – 5,850 vph ♦ Five mainline lanes in one direction – 7,450 vph ♦ Six mainline lanes in one direction – 9,050 vph ♦ More than six mainline lanes in one direction – 10,650 vph
6	Volume 2	Is the ramp volume plus the mainline right lane volume downstream of the gore during the peak period greater than 2,100 vph?
7	Geometry 1	Is sufficient acceleration distance available? If no, can minor geometric improvement provide required length?
9	Geometry 2	Is there sufficient storage distance? If no, can minor geometric improvements provide the required length?

The manual also recommends considering impact of diversion, taking into consideration public opinion, and providing equity between ramps by including additional upstream ramps. According to this document, NDOT uses 2–5 second green and 2–30 second red intervals for meter signals. In additional metering levels vary according to freeway speeds. The manual also emphasizes the need for identifying current and future funds related to the planning, design, construction, administration, and maintenance of ramp meters prior to deployment.

Part 3 of NDOT *Managed Lanes and Ramp Metering Manual* (*31*) presents design considerations, including number of lanes, location of stop bar, enforcement area, acceleration

distance, storage distance and lane markings, equipment, and sensors. The following list reproduces key items:

- CCTV is required to monitor ramp meter operation and must be able to provide a view of all ramp lanes, ramp queue, and adjacent ramp terminal intersection.
- Loop detectors are required. Other types can be used with NDOT permission.
- Trailing edge of demand detector must be 3 ft downstream of stop bar.
- Leading edge of passage detector must be 15 ft from the stop bar.
- Advanced queue detector must be 100 to 300 ft from arterial's curb line.
- Mainline detectors should be typically placed 500 ft upstream of the entrance ramp gore area and provide occupancy, speed, and volume information for use in various algorithms.
- Exit ramp detectors are used for systemwide traffic responsive metering and freeway management systems.
- Cabinet should be placed where it is easy to access and allow crew to see signal heads, typically on the right side of ramp.
- A mast arm style signal pole with overhead signal head must be used on all metered ramps. All poles should be placed outside of clear zone or protected by barrier or guard rail. Signal head should have a min of two faces (red and green). Distance from stop bar to signal is typically 60 ft.

Part 4 of the manual (*32*) presents guidance on system monitoring, the objective of which is to track changes in performance over time, to identify meters with performance issues and identify solutions, to provide information to decision makers and public, to assist in resource allocation, and to assess benefits against costs. The following list identifies recommended performance measures:

- Average cycle length.
- Average service-flow-rate.
- Average total flow rate.
- Freeway speed.
- Ramp meter efficiency (metered flow/total flow, if 1 all traffic is metered).
- Average number of flushes.
- Average time to first flush.
- Average and maximum flush durations.
- Mean time between flushes.
- Impact on adjacent facilities.
- Safety assessment using crash records.
- Travel time reliability.
- Congestion duration.
- Emissions and fuel consumption, and associated tradeoffs between freeway and ramps/surface streets.
- Ramp queue.
- Public opinion survey.

WASHINGTON DOT

As per information published on the Washington State Department of Transportation (WSDOT) webpage (*33*), the objective of ramp metering is to reduce collisions and decrease travel times for commuters. Most WSDOT ramp meters operate in a one-car-per-green mode, creating a 4–15 second delay between cars entering the highway. When possible, the department provides non-metered HOV bypass lanes for buses, carpools, and vanpools. Typical ramp meter operation times are 6 a.m. to 9 a.m. and from 3 p.m. to 7 p.m. but can vary depending on the level of traffic congestion. WSDOT uses magnetic loops and radar for detection of traffic speeds and volumes on highway lanes and ramps. These data are communicated to the TMC and the ramp meters to automatically implement optimal metering rates to maximize traffic flow on both the ramps and the freeways. Ramp metering has resulted in system-wide crash reduction of 30 percent and travel-time savings of 3 to 16 minutes.

WSDOT has the following design requirements and policies related to ramp metering (*34*):

- All on-ramps within the Seattle metropolitan area shall have a ramp meter installed.
- On-ramps outside of the Seattle metropolitan area shall have a ramp meter installed when the sum of the volume in the right lane of the mainline and the volume of the on-ramp equals or exceeds 1700 vph during the peak hour in the year when operation begins.
- Ramp meters shall be designed as a system. If a roadway has three on-ramps near the upstream-most and downstream-most on-ramps qualifying for a ramp meter, the remaining on-ramp shall also be equipped with a ramp meter. This is to discourage diversions from metered ramps onto adjacent non-metered ramps.
- Acceleration distance must be sufficient to allow metered vehicles to reach freeway operating-speeds. The designer shall consider gradient, mainline speed characteristics and flow breakdown characteristics, horizontal curvature, and heavy vehicle needs when determining acceleration distance. Designers shall ensure that the acceleration distance from the stop line is short enough to prevent vehicles released at separate intervals from being able to regroup before merging.
- The ramp meter shall be placed as close to the downstream end as possible. This is to maximize storage capacity and provide adequate sight distance to the ramp meter signal.
- Sufficient storage needs to be provided to prevent ramp queues from extending beyond the entrance of the ramp and into upstream intersections. Storage requirements depend on ramp demand, demand distribution, metering strategy. In determining storage requirement through modeling, the designer shall use 20-year demand projection beyond initial meter operation. Furthermore, storage on any ramp shall not be less than 450 ft per lane. HOV volume shall not be subtracted from the peak hour volume when calculating ramp storage. Ramp meter rates are adjusted to subtract HOV volume from the number of vehicles processed by the meter each minute. The result is that the storage needed remains the same as if the HOV traffic had waited in the queue.
- When it is not feasible to increase storage capacity by lengthening the on-ramp, storage capacity can be increased by adding lanes.
- A minimum of 1 metered lane shall be provided when the current peak hour volume is less than or equal to 600 vph.

- A minimum of 2 metered lanes shall be provided when the current peak hour volume is between 601 and 1,200 vph.
- A minimum of 3 metered lanes shall be provided when the current peak hour volume is over 1,200 vph.
- To keep costs low, a hard shoulder together with minor widening may be converted to a metered lane.
- Maintenance activities require both access to the contents of ramp meter cabinets and visual confirmation of ramp meter operations, often concurrently. Therefore, it is beneficial to place the cabinet so that the signal heads are visible from the cabinet, a configuration that will require just one maintenance person to perform basic maintenance duties rather than two (one for cabinet work and the other for visual confirmation).
- At a ramp meter, the maximum detector lead-in length for mainline loops and stop line loops (demand and passage) is 500 ft. The maximum detector lead-in length for all other loops is 800 ft.
- The ramp meter signal pole (to be used only for single-lane meters) shall be visible to drivers as they approach the signal for a minimum of 300 ft, located no more than 8 ft from the edge stripe and adjacent to the lane it is metering and accompanied by appropriate signing. A pole placed closer than 5 ft from the edge stripe shall be behind or on top of a barrier.
- The Overhead Ramp Meter Signal Standard may be used for ramp meters with one lane and shall be used for all ramp meters with two or three lanes and must be accompanied by appropriate signing.
- Advanced warning sign together with a flashing beacon is required and each approach shall have a clear view of advanced warning sign before drivers commit to the ramp.

Researchers also obtained the following additional information from WSDOT staff:

- Currently WSDOT has 180 ramp meters, most of which are dual-lane.
- Installation cost is $110 for a data station and $130K for a ramp meter installed on existing pavement. Any civil costs are in addition to these.
- Allocation of human and financial resources for yearly maintenance and operations:
  - Estimated maintenance 20 man-hours/ramp meter/year.
  - Estimated operation cost is 3 man-hours/ramp meter/day.

WSDOT's success with ramp metering is due to a comprehensive program that includes maintenance, operations, performance monitoring, and cooperation with stakeholders. WSDOT's maintenance activities are rolled in with other similar activities such as traffic signals, other ITS devices such as cameras, and VMS. Operational activities depend on the concept of operation, level of integration with the surrounding systems, sophistication of control algorithm, and level of involvement of the system operators. WSDOT provides dedicated staff to perform maintenance and operation of ramp meters. This practice prevents other maintenance activities (such as traffic signal operation) from taking priority over ramp meters. Another key factor contributing to WSDOT's success with ramp metering is the ability to rally internal and external support necessary for deploying and operating ramp meters. Lastly, WSDOT collects performance measures necessary for establishing operational and safety benefits of ramp metering. These measures include volume, occupancy, speed, travel time, travel time reliability,

and crash data. To oversee these activities, WSDOT uses a lead engineer with good interpersonal skills, strong operations background, and willingness to learn from peer states that have strong ramp management programs. The department also takes advantage of FHWA's peer-to-peer program supporting these types of exchanges.

MODELING APPROACHES

TRAFFIC ACTIVITY MODELING

Three types of tools are available for traffic activity modeling. This section provides a discussion about the characteristics and capabilities of these traffic models.

Macroscopic Models

Macroscopic travel demand models (TDMs) are planning models that incorporate geographic information systems (GIS) designed specifically for use by transportation professionals to display, analyze, and store transportation data. A TDM contains various application modules for routing; travel demand forecasting, logistics, and site management by incorporating multiple trip purposes; and modes of traffic. It provides the network blueprint of all roadways and contains an origin-destination (OD) matrix, which it uses to assign trips between zones based on land use and household demographic data. TDMs typically follow a sequential four-step process, which includes the following steps:

1. Trip generation – determines the number of trips generated between OD pairs.
2. Trip distribution – determines where trips are going.
3. Mode choice – identifies the travel mode used for each trip.
4. Assignment – determines the routes travelers choose to reach their respective destinations.

Macroscopic models combine GIS with transportation modeling functions to create and customize maps, build and maintain geographic data sets, and perform different types of spatial analyses. Software in this category include TransCAD (*35*), VISUM (*36*), EMME2 (*37*), CUBE Voyager (*38*), and Aimsun (*39*).

Mesoscopic Models

Mesoscopic models are regional simulation-based models that use DTA. DTA is a time-dependent methodology, which captures traveler's route choice behavior as they traverse between origins and destinations. The objective function, known as Dynamic User Equilibrium (DUE), provides for drivers choosing their routes through the network according to their generalized travel cost experienced during the simulation. A generalized cost includes both travel time and any monetary costs (e.g., tolls) or other relevant attributes associated with a roadway. An iterative algorithmic procedure attempts to establish DUE conditions by assignment vehicles departing at the same time between the same OD pair to different paths. At any given point and after much iteration, travelers learn and adapt to the transportation network conditions. In literature, there are two major DTA model categories: analytical and simulation-based DTA. Most of the existing commercially available models are simulation-based because simulation-based approaches are generally more flexible than analytical DTA models in accounting for various network traffic conditions such as traffic signals, incidents, and driver routing behaviors (*40*). A simulation-based DTA model typically consists of two principal model components: a simulation model and a traffic assignment model. The simulation model is aimed at evaluating the quality of the assignment solution and the assignment model takes the inputs from the

simulation to further generate more paths and assign vehicles to different paths to get close to DUE condition over multiple iterations.

Simulation Model

Most existing DTA models adopt a mesoscopic traffic simulation approach in which individual vehicles' position and speed are calculated based on average traffic conditions on the link following either macroscopic speed-density relationship, headway distributions, or queuing processes. Mesoscopic simulation models generally have coarser simulation time resolutions (in the order of 5–10 seconds as opposed to 0.1–1 second time-steps in microscopic models). In some instances, driver responses to changes in roadway configurations are also simplified through changes in link capacities. With the simplified simulation logic and coarser time resolution, a mesoscopic model can accommodate a much larger network with more vehicles and longer simulation periods compared with microscopic models. In addition, all DTA models perform path-based simulation, meaning that each vehicle follows an assigned path from the origin to the destination. Traffic diversion in response to changes in roadway traffic conditions or information provided to the drivers may also be modeled.

Traffic Assignment Model

The traffic assignment model is another critical component of the DTA model. The term assignment can be interpreted as assigning vehicles to routes following a specific objective. Vehicles with different routing objectives may be assigned with different routes computed with different respective objectives. The assignment model is generally an iterative numerical procedure, involving both analytical calculations and heuristics that are aimed at achieving DUE conditions. The DUE condition can be generally defined as the traffic condition in which those who travel between the same OD pair at the same departure time taking different routes will experience the same travel time. No one can unilaterally improve their travel time without increasing the travel time on other routes at the DUE condition. This definition highlights the key features required by the assignment model. First, experienced travel time needs to be captured. This means not only a traffic simulation approach is needed, but also a time-dependent (experienced) shortest-path (least-cost algorithm) is needed to compute the shortest path with least experience travel time or cost. The traditional instantaneous shortest path algorithm relies on the link travel time at the time instance at which the shortest path is calculated. Second, the traffic state temporal inter-dependence needs to be captured. This is critical from modeling the traffic dynamic continuity standpoint. All traffic simulation models maintain such temporal continuity; however, certain time-sliced static traffic assignment approaches that fall short in maintaining the temporal state inter-dependence may produce inconsistent and counterintuitive results when examined from the traffic flow perspective. Available models in this category include DynusT (*41*), DYNASMART-P (*42*), Dynameq (*43*), VISTA (*44*), TransDNA (*45*), AIMSUN (*39*), CUBE Avenue (*46*), and INTEGRATION (*47*).

Microscopic Models

A microscopic simulation model describes both the system entities and their high level of detail. The details of microscopic models yield the flexibility to add many more modeling contexts and options than mesoscopic and macroscopic models. Microscopic models, though requiring more

computing time and resources to run, can represent vehicles more realistically than macroscopic or mesoscopic models. These types of simulation models theoretically are more responsive to different operational strategies and can produce more-accurate measures-of-effectiveness and provide enough flexibility to test various combinations of supply and demand roadway management strategies. Microscopic traffic simulation models are usually time-step and behavior based that replicate vehicular traffic and public transportation. These models can analyze traffic and transit operations under constraints such as specific lane configuration, various vehicle compositions, traffic control strategies, and transit terminals thus making them useful tools for the evaluation of assorted alternatives based on transportation planning and traffic operation needs. In the context of ramp metering, microscopic models can simulate various types of traffic control strategies including single lane versus dual ramp entry, specialized signal timing algorithms, and queue flushing. Microscopic model include but not limited to CORSIM (*48*), Paramics (*49*), VISSIM (*50*), AIMSUN (*39*), and TransModeler (*51*).

Multiresolution Modeling

Multiresolution modeling (MRM) captures the spatial and temporal aspects of modeling at both the regional and localized levels simultaneously by integrating software designed for modeling at different levels of resolution (macroscopic, mesoscopic, and microscopic). MRM allows one to synergize the strengths of multiple models by retaining the best characteristics of each.

The premise to using the MRM process over traditional macroscopic static assignment methods is the use of DTA. Traditional planning methods use static long-range models to analyze traffic redistribution given network changes. However, since static models only give an average of traffic flow on each link for the entire simulation time horizon, it is unable to capture the temporal and spatial distribution of traffic at any given time. The DTA model reflects that system structural pattern of traffic during peak and off-peak hours. Converting data from mesoscopic to microscopic over the traditional macroscopic to microscopic is thus more advantageous. The mesoscopic to micro conversion process follows the same conservation of flow at any given time, making this methodology more robust in realistic network representation.

MRM is used when analysis is needed at both the localized and regional levels. The MRM process is often used when microscopic analysis capabilities are needed (e.g., individual lane level) but the corridor is too big (i.e., corridor with multiple entry and exit locations) to simply develop by hand. The use of the MRM platform allows researchers and practitioners to create large-scale microscopic models for various operational planning scenarios. Normally, large-scale microscopic models take tremendous time and resources to calibrate. A direct conversion under the MRM principles correlates to a more robust representation of the corridor. For example, a large network can be coded into microscopic simulation software relatively quickly but developing the OD pairs within the network requires substantial time and effort. However, using a conversion tool that is capable of not only translating the network geometry (links, nodes, and zones) from one level of resolution to another but also transferring over the time-dependent paths and flows for each OD pair is a great achievement. The Texas A&M Transportation Institute (TTI) has developed a conversion tool that translates mesoscopic subareas to microscopic format (DynusT to VISSIM) and macroscopic to mesoscopic (VISUM to DynusT).

Traffic Data

All models need data to populate their respective platforms. TDMs require socioeconomic data including income, household size, number of vehicles, zonal structure, trip purposes, roadway functional classes, and the roadway network. While macroscopic models may be considered the foundation of all subsequent modeling resolutions, there is no temporal aspect (i.e., no time component) so they only estimate overall averages for a given time period. In order to incorporate the temporal component of modeling needed for emissions analysis, a simulation-based modeling platform is needed—both at the localized and regional levels. Therefore, mesoscopic and microscopic models will be used to simulate traffic conditions in and around the study areas of concern. Traffic counts (volumes) will be needed to calibrate the OD matrices along specified corridors so the models will reflect actual traffic conditions. If the study includes intersections (e.g., diamond interchanges adjacent to freeway facilities), signal timing plans should be incorporated into the simulation platform. Speed (microwave) and travel time (Bluetooth) data for specified corridors are used to validate simulation outputs. Probe vehicles can also be used to validate travel times on specific corridors. Once the models are reasonably calibrated and validated with field data, various ramp-metering scenarios will be tested. Each scenario simulation result will use time-dependent speed, density, and flow outputs as inputs for MOVES.

Ramp Metering

Ramp metering in DTA models limit the rate at which vehicles enter the freeway facility by preventing total traffic to stay below downstream mainline capacity. Thus, excess demand is either stored on the ramp or diverted to adjacent roadways. The diverted vehicles may choose less traveled alternative routes with shorter experienced travel times. Metering rates range from a lower limit (i.e., 240 vph) to a practical maximum value (i.e., 900 vph). From a modeling perspective, the software adjusts on-ramp flow rates based on upstream freeway flow and downstream capacity of mainline freeway lanes. DynusT ramp metering algorithm follows a logic derived feedback control algorithm (*52*). The original procedure measures the flow on freeway mainline lanes downstream of the ramp and determines the remaining freeway capacity available based on downstream occupancy values. In this algorithm, real-time on-ramp flow is adjusted to meet the available capacity. The model formulation is (*53*):

$$\gamma_t = \gamma_{t-1} + \alpha(\beta - MDO)$$

where:

γ_t : Ramp flow rate (veh/hr/lane) for the tth period
γ_{t-1} : Ramp flow rate (veh/hr/lane) for the $(t-1)^{th}$ period
MDO : Measured downstream occupancy (percent time)
α : Occupancy-to-flow conversion rate (veh/hr/lane/percent time)
β : Maximum freeway downstream occupancy (percent time)

$$\gamma_t = \begin{cases} Saturation\ flow\ rate\ (SFR)\ if\ \gamma_t \geq SFR \\ 700\ veh\ per\ hour\ per\ lane\ if\ \gamma_t < SFR \end{cases}$$

The term $(\beta - MDO)$ represents the downstream capacity available for entering vehicles. Therefore, the higher the β is, the more capacity is available for entering vehicles. The term α is the control factor, which controls the number of vehicles entering the freeway through the on-ramp. Therefore, the higher α is, the higher the number of vehicles entering the freeway.

At the microscopic level, ramp-metering implementation closely resembles a real traffic controller, where control logic uses lane-by-lane detections of individual simulated vehicles to control a simulated signal at time resolutions of up to one-tenth of a second. VISSIM provides a variable actuated programming (VAP) language, which users can use to develop any control logic varying from simple to very complex algorithms. The simplest control logic consists of a ramp signal, and a sensor upstream of it. The simulated controller changes the signal to green, yellow, and red indications of specified lengths to meter a detected vehicle. The sum of these intervals determines the maximum metering rate. The signal dwells in red when there is no vehicle at the signal. Figure 7 shows a single lane metered ramp represented in microsimulation.
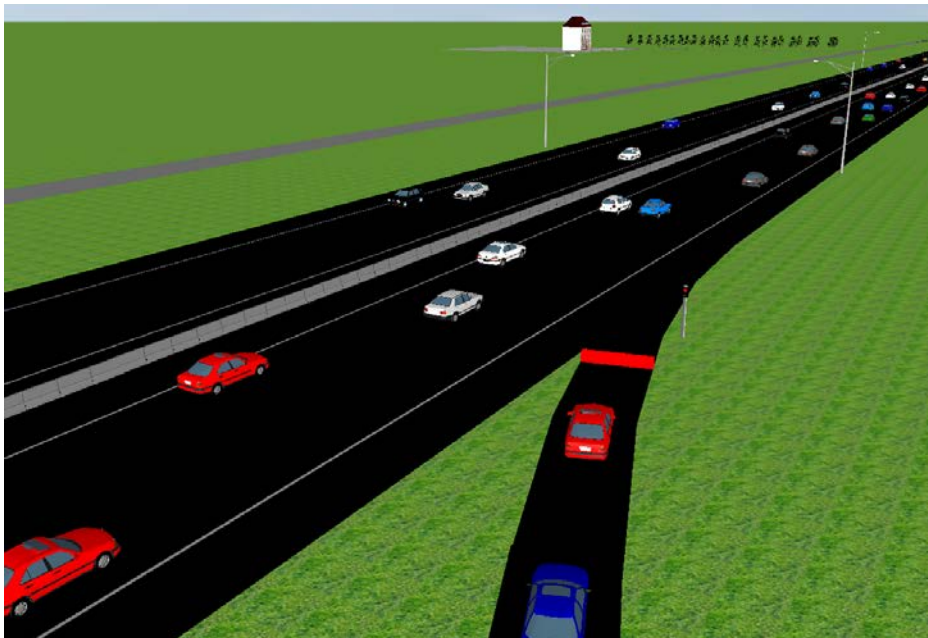
Figure 7. Single Lane Ramp Meter Microscopic Simulation.

EMISSIONS IMPACT OF RAMP METERING

This section reviews information relevant to the assessment of the emissions impact of deploying ramp metering. This research project investigated if ramp metering can be deployed to alleviate freeway traffic congestion and improve air quality, with an emphasis on the DFW region as a case study. Therefore, a brief overview of regulatory requirements pertaining to transportation air quality and the current air quality status in the DFW region is provided. This is followed by an overview of current state of the practice in assessing emissions impact of ramp metering, available emissions models, and data needs for both model-based and non-model-based emission estimation methods. Finally, a summary of available traffic data sources that could be used for identifying optimal ramp metering location and analysis of emissions impacts of ramp metering is also provided.

Transportation Air Quality Regulations and Status of the DFW Region

Background

The Clean Air Act (CAA) is the federal law regulating emissions and air quality in the United States. The CAA was originally enacted in 1970 and authorized the Environmental Protection Agency (EPA) to establish National Ambient Air Quality Standards (NAAQS) for pollutants harmful to public health and welfare. The NAAQS are subject to periodic review and update. Areas not meeting the NAAQS for a specific pollutant are designated by the EPA as nonattainment areas (*54*). These areas require the State Air Agency—Texas Commission on Environmental Quality (TCEQ) in the case of Texas—to adopt enforceable air quality plan known as the state implementation plan (SIP), to achieve and maintain air quality levels meeting the NAAQS. The enforcement mechanism for the on-road mobile source portion of SIPs is based on a process that is commonly known as transportation conformity.

The transportation conformity requirements currently in effect are based on the 1990 amendments to the CAA. They apply to nonattainment areas (areas that currently do not meet NAAQS levels) and attainment-maintenance areas (areas that currently meet the NAAQS but had a NAAQS violation in the past 20 years) (*55*).

Transportation conformity can broadly be viewed as a process of linking transportation planning (conducted by state DOTs and metropolitan planning organizations [MPOs]) with air quality planning as reflected in the SIP. The intent of transportation conformity is to ensure that the projects, programs, and policies identified in transportation plans and transportation improvement programs are consistent with air quality goals (*55*).

Conformity requirements may include a cap on on-road mobile source emissions for a pollutant from an area established in the SIP, known as motor vehicle emission budget (MVEB). In addition to MVEB, the SIP may also include control strategies being implemented, or considered for implementation to enable the region to meet the NAAQS. The on-road mobile source control strategies included in the SIP are called transportation control measures (*55*). Transportation control measures are transportation projects and programs identified as having emission reduction benefits. For MPOs demonstrating transportation conformity, emission reduction plays an important role as they can use the benefits to meet the SIP MVEB.

In light of this, it is important for state and local agencies in nonattainment areas to look for travel demand management and traffic management strategies and approaches to reduce mobile source emissions. These strategies include bicycle-pedestrian facilities, transit, dynamic messaging, traffic signal improvements, ramp meters, etc.

Texas Nonattainment Areas and DFW Region Status

Both the major metropolitan areas in Texas, the Houston-Galveston-Brazoria region and the DFW region, have historically been in nonattainment for ozone. Ozone is a secondary pollutant formed in the atmosphere through a complex chemical reaction between NOx and VOC in the presence of sunlight.

In the case of the DFW region, four DFW area counties (Dallas, Denton, Collin, and Tarrant) were initially designated following the 1990 CAA amendments as being in moderate nonattainment of the one-hour ozone standard of 0.12 ppm. On March 27, 2008, EPA strengthened the primary and secondary eight-hour ozone standard to 75 ppb (73 FR 16436). On May 21, 2012, EPA published in the Federal Register (77 FR 30088) final designations for the 2008 eight-hour ozone standard. A 10-county DFW area including Collin, Dallas, Denton, Ellis, Johnson, Kaufman, Parker, Rockwall, Tarrant, and Wise Counties is currently designated nonattainment and classified moderate under the 2008 eight-hour ozone standard, effective since July 20, 2012. The attainment deadline for the DFW moderate nonattainment area is July 20, 2018 (*56*). On October 23, 2015, EPA published the final rule (80 FR 52630) revising the 8-hr ozone NAAQS to 70 ppb with nonattainment designations anticipated in late 2017. On June 21, 2017, EPA extended by the deadline for promulgating initial area designations for the ozone to October 1, 2018 (EPA-HQ-OAR-2017-0223).

From the 2008 Eight-Hour Ozone Attainment Demonstration SIP Revision for the 2017 Attainment *Year* developed by TCEQ, a significant portion of NOx emissions in the DFW area is generated by on-road mobile sources. Given the increasing levels of vehicle activity in urban areas on-road emissions will remain a major part of the regional emissions inventory, and the reduction of on-road mobile source emissions will continue to be important to meet air quality goals.

Ramp Metering as an Emissions Reduction Strategy

Ramp metering is a traffic management strategy that has been demonstrated to alleviate congestion on freeways by restricting the volume of traffic entering the freeway, and by breaking up large platoons of vehicles that would otherwise attempt to join the freeway in close succession (*57*). Numerous studies have shown that in addition to improving traffic flow at peak travel times, ramp metering can reduce congestion and delays caused by factors such as lane closures, insufficient exit capacity, and accidents. Studies have shown that the improved traffic flow that occurs because of ramp metering, particularly the reduction of stop-start conditions, could lead to reductions in fuel consumption and emissions.

According to the U.S. Department of Transportation synthesis report, highway traffic management strategies and real-time traveler information, including signal timing, freeway ramp metering, faster clearance of incidents, and variable message signs, have modest potential for reducing greenhouse gas emissions (*58*). A corridor-level study conducted by Pukyong National University researchers estimated emissions before and after a locally controlled ramp metering device (allowing four vehicles every 30 seconds) was installed on a South Korean overpass with heavy congestion during peak hours. The simulation study on a 10.15 km two-lane urban highway showed that while the emissions of vehicles on-ramps were increased, there was a 7.3 percent net reduction in overall carbon dioxide (CO_2) emissions considering sections of main lane, on-ramp, and detour routes (*59*).

A research project conducted by University of Minnesota researchers for MnDOT in 2002 in Minneapolis used Traffic Management Laboratory for assessing the effectiveness of MnDOT's control strategy in three Twin Cities freeway sections totaling approximately 65 miles. The results showed an up to 34 percent reduction of net fuel consumption, 18 percent reduction in

CO emissions, 14 percent in hydrocarbons (HC) emissions, and 26 percent in NOx emissions (*60*).

In a study by a team of consultants, a ramp metering evaluation of a section of l-35 south of Minneapolis conducted in 2000 focusing on incremental change observed between two evaluation scenarios: with ramp meters and without ramp meters. Data were collected from four interstate corridors in the Twin Cities area. The study concluded that ramp metering resulted in an increase of fuel consumption while reducing emissions. These contradictory results are potentially a result of not considering the "impact of more erratic acceleration/deceleration on freeways resulting from slower speeds, more congestion, and less predictable traffic conditions" in their analysis (*61*).

A 1999 study of ramp metering in Atlanta used a modal emission model to estimate the emissions and fuel consumption before and after ramp metering. The results varied for different pollutants, the study showed a 21.3 percent reduction at ramp, 12.7 percent reduction at weaving section, and 1.3 percent reduction in mainline in NOx emissions during peak hours. On the other hand, it showed a 44 percent increase at ramp, 49 percent at weaving section, and 1.4 percent reduction in mainline in CO emissions during peak hours as well (*62*). A 1999 study of ramp metering by the California PATH program used speed based emission rates from the EMFAC7G model and temporal travel demand and speed change based on the average travel pattern obtained from the I-880 freeway database to show that the net emission reduction in CO and HC, including ramp and mainline, would be positive at the first three years after the installation of ramp metering. From a long-term perspective, the study showed that ramp metering could increase emissions in later years if it cannot be adaptive to the increase of ramp queues and traffic growth (*63*).

Long Island, New York, project INFORM (Information For Motorists) covered a 64 km long by 8 km wide corridor at the center of which is the Long Island Expressway. This 1989 study included a total of 207 km of roadways involving 70 metered ramps along the Long Island Expressway. Motorists entering at metered ramps experienced an overall travel time reduction of 13.1 percent and an increase in average speed from 37 to 45 kph. The study also estimated that fuel consumption was reduced by 6.7 percent, a 17.4 percent reduction in CO emissions, 13.1 percent reduction in HC, and 2.4 percent increase in NOx emissions two months following (*64*).

Overall, the studies reviewed in this section indicate that there are potential fuel and emission reduction benefits from ramp metering. However, the findings are not conclusive, and questions remain about the overall emissions reduction possible and the applicability of these benefits over time.

Evaluation of Ramp Metering Emission Impacts

Emissions Modeling Overview

Estimating emissions from on-road mobile sources, and the assessment of emissions impacts of traffic-related strategies make use of emissions modeling at different scales. The emissions modeling process can be broadly viewed as combining information on vehicle activity and

vehicle emissions to estimate overall emissions impacts. Similar to traffic modeling, the underlying methodologies and approaches for emissions modeling range from macroscopic to microscopic levels. Macroscopic emissions estimation methodologies use average regional parameters to estimate energy consumption and emission factors. Microscopic emission estimation methodologies estimate vehicle fuel consumption and emission factors, which are based on second-by-second operating conditions of vehicles such as instantaneous speed and acceleration (*65*).

The emission estimation methodologies used for regulatory purposes such as the regional emissions analysis for transportation conformity are generally macroscopic in nature, estimating emissions at a regional scale. However, some type of microscopic emissions information based on finer scale measurements is also used to better represent real world conditions and traffic activity. For example, two identical vehicles operating with the same average speed will generate different emissions based on stop, start, and acceleration movements. To account for this, macroscopic analyses may still use microscopic emissions models that estimate traffic specific conditions or emission factors based on drive cycles specific to different road types, vehicle classes, and traffic conditions. In many cases, the drive cycle-based approach is desirable because it does not require significant levels of highly accurate traffic movement data (*66*).

Some of the early microscopic emissions models are the Comprehensive Modal Emissions Model and the Virginia Tech Microscopic Energy and Emission Models. The EPA's newest emission model, MOtor Vehicle Emission Simulator (MOVES), has emerged as the preferred emissions modeling platform for a range of regulatory and research purposes. EPA has mandated the use of MOVES for all official air quality estimations in United States, except for California. MOVES has improved capabilities compared to its predecessors and has replaced the EPA's MOBILE macroscopic emission model for regulatory emission estimation purposes (*66*).

MOVES provides a suitable platform for analysis of emissions impact of ramp metering because it is a modal-based model that estimates emissions based on a unique combination of modes (or bins) that represent vehicle operating conditions and vehicle characteristics. MOVES uses 40 drive cycles to model a wide range of possible driving patterns and their resultant emissions. The flexible database structure of MOVES allows for further customization of the drive cycles in MOVES for emissions analyses. Thus, customizing the drive cycles in MOVES using local data for the specific project or region can serve to improve regional emissions estimates. Studies have shown that it is important to incorporate such local specific travel activity as the driving characteristics of each area are unique due to different vehicle fleet composition, driving behavior, and road network topography (*67*). The latest version of MOVES is MOVES2014a (released by the EPA in November 2015) was used for this study.

MOVES Model Capabilities and Data Needs

MOVES is a microscopic emissions model that uses a fine-scale modal-based approach to generate emission and energy consumption factors at different temporal geographical scales (national, county, and project). MOVES includes emission factors for different subsources including exhaust (running, idling, and start), brake wear, tire ware, and crankcase emissions (*67*).

MOVES uses a factor called vehicle specific power (VSP), which is a combined measure of instantaneous speed, acceleration, road grade, and road load. For medium- and heavy-duty vehicles, VSP is converted to another factor called scaled tractive power. VSP and scaled tractive power are calculated on a second-by-second basis for a vehicle operating over a specific speed trajectory (i.e., drive cycle) (*68*). The emissions associated with any given drive cycle and vehicle type are modeled based on distribution of time spent in operation mode bins (opMode bins). OpMode bins are defined according to second-by-second speed and VSP or TSP. This process is graphically demonstrated in Figure 8.
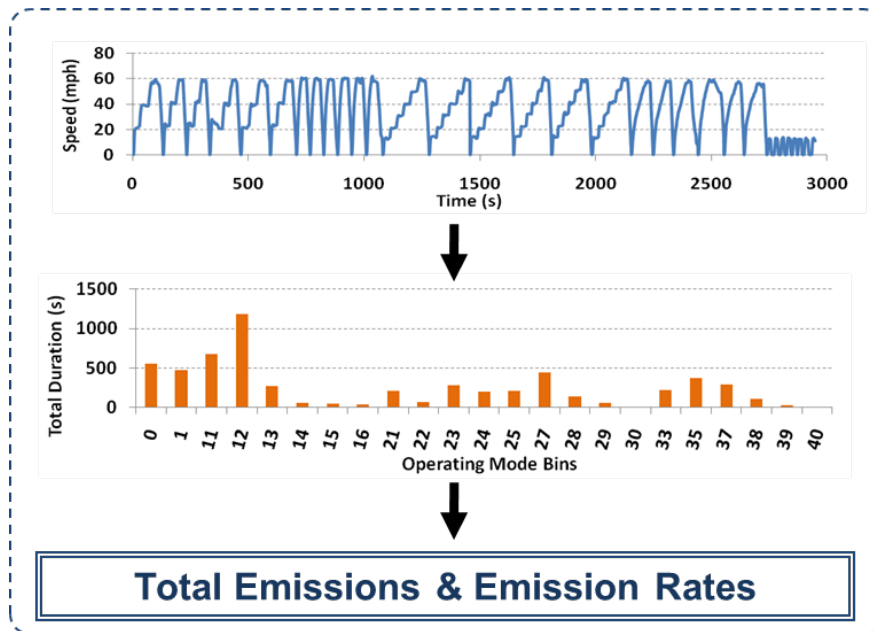
Figure 8. Emissions Estimation Process in MOVES.

MOVES is designed around a database that contains up to date information for vehicle types, ages, fuel types, and the emissions parameters relevant to them. This design allows considerable flexibility in terms of analysis level and using local input parameters. MOVES's database includes a set of 40 drive cycles representing a wide range of traffic conditions and average traffic speeds for 13 vehicle types (Table 6) and four roadway categories (Table 7). Users can also create and use their own local drive cycles. This feature is specifically helpful for project-level analyses that deal with changes in traffic patterns.

Table 6. MOVES Vehicular Source Types.

Vehicle Class	Source Type ID	Description
Light Duty	11	MotorCycle
	21	Passenger Car
	31	Passenger Truck: SUV, Pickup Truck, Minivans - Two-Axle/Four-Tire Single Unit
	32	Light Commercial Trucks - Two-Axle/Four-Tire Single Unit
Buses & Medium-Duty	41	Intercity Buses
	42	Transit Buses
	43	School Buses
	52	Single-Unit Short-Haul Trucks
	53	Single-Unit Long-Haul Trucks
	54	Single- Unit Motor Homes
Heavy Duty	51	Refuse Trucks
	61	Combination Short-Haul Trucks
	62	Combination Long-Haul Trucks

Table 7. Summary of MOVES Road Types for Moving Vehicles.

Road Type ID	Description	HPMS Functional Type
2	Rural Restricted Access	Rural Interstate
3	Rural Unrestricted Access	Rural Principal Arterial, Minor Arterial, Major Collector, Minor Collector, and Local
4	Urban Restricted Access	Urban Interstate and Urban Freeway/Expressway
5	Urban Unrestricted Access	Urban Principal Arterial, Minor Arterial, Collector, and Local

A valuable feature for this project in MOVES is the ability to support both county level (regional) and project level emissions assessments. For regional scale emissions assessments, aggregated county level activity and fleet characteristics information will be used. The emission factors obtained from the MOVES model can be combined with vehicle activity to estimate total emission (equation1) for all roadway links in the regional. The type of vehicle activity depends upon the emission process, for example, to model running exhaust emissions, the relevant vehicle activity is vehicle miles traveled (VMT); while start exhaust emissions is modeled using the number of vehicle starts, and emissions from idling are modeled using vehicle idle time.

$$Total\ Emissions = Emission\ Factors\ \times Vehicle\ Activity\ Measure$$

The MOVES project-scale analysis function is the most spatially explicit modeling level in MOVES as it calculates emissions from a single roadway link or a group of specific roadway links. For project level emission assessment, MOVES requires inputs from two broad categories illustrated in Figure 9:

- Site-specific traffic information, including traffic volumes, fleet composition, and vehicle activity at the roadway link level.
- Local-specific inputs, including regional-level vehicle age distribution meteorology, fuel supply, and inspection/maintenance (I/M) program parameters.
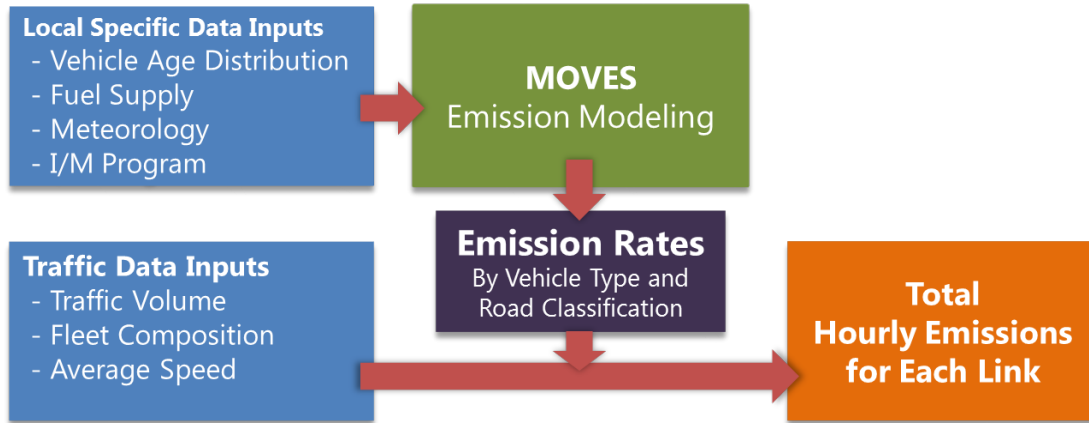
Figure 9. MOVES Emission Modeling.

With few exceptions in MOVES inputs and different aggregation levels, the data sources used for project-level and county level emission assessments are similar. Table 8 summarizes the input data requirements and possible sources for project-level analyses using MOVES.

OTHER METHODS USED FOR EMISSION ESTIMATION

Other methods that can be applied to assess emissions impacts of ramp metering include the use of standardized equations in what is termed as an off-model approach. These methods generally allow for the estimation of individual mobile source emission reduction strategies, using computations performed outside of a simulation models by applying generalized sketch-planning techniques. Texas Guide to Accepted Mobile Source Emissions Reduction Strategies (MOSERS manual) and other similar established methods are predominantly used by planners for estimating emission benefits for various strategies in their SIP, conformity, and voluntary programs and actions (*68*).

These approaches require inputs such as VMT reductions, speed improvements, idling duration reduced, etc., which are specific to the strategy and emission factors to estimate emissions. Data sources for these inputs range from those that are easy to acquire from local data or knowledge to those that may require specialized surveys or field data collection. In the absence of local data, informed assumptions based on practitioner knowledge can be used.

TxDOT, MPOs, transit agencies, city DOTs, and other local agencies are all valuable sources of data and information. TxDOT, for example, performs local traffic counts statewide and is a valuable source of basic traffic volume information. City DOTs and MPOs may also have traffic volume data. Other important sources of data include regional TDM outputs, other traffic analysis data, census data, and local travel surveys. Current emissions models such as MOVES can provide emissions factors needed for many of the emissions-related variables. The final unit of measure for each strategy is grams per day (*68*).

Table 8. Input Data Requirements for MOVES Project Analysis.

Data Item	Description	Source
Link	Roadway link characteristics	User defined
Average Speed	Average speed at the roadway link level specific to the vehicle type	TDMs, Statewide Traffic Analysis and Reporting System (STARS-II) database, or emerging sources of data (INRIX or National Performance Research Data Set [NPMRDS])
Link Drive Schedule	Vehicle trajectory or speed/time trace	Traffic microsimulation models. Link drive schedule is optional for roadway links if the average speed data are provided.
Operating Mode Distribution	Specifies amount of time spent by vehicle fleet in different operating modes	Operating mode distribution is optional for roadway links if the average speed or link drive schedule data are provided. MOVES includes default Operating Mode Distributions based on typical driving cycles.
Link Source Type Fraction	Link specific percentage of link traffic volume driven by each vehicle type	STARS-II database and local classification data
Source Type Age Distribution	Vehicle age distribution	Department of Motor Vehicles vehicle registration
Meteorology	Temperature and humidity	TCEQ data
Fuel Supply	Fuel supply parameters and associated market share	TCEQ and the EPA's latest available summer season retail outlet reformulated gas survey data in major Texas metropolitan area
Inspection-maintenance Program	I/M program parameters for nonattainment areas	Texas State I/M rules I/M parameters from MOVES database
Off Network Link	Represents vehicle start, short-term idling, and extended idling emissions	Local specific data TDMs

AVAILABLE TRAFFIC DATA

Traffic data required for traffic performance and emissions analyses include traffic volumes, speeds, travel time, fleet composition, and roadway geometry. Source of these data include:

- TDMs.
- The Highway Performance Monitoring System (HPMS).
- TxDOT STARS-II.
- NPMRDS.
- INRIX data.
- TxDOT Vehicle Detection Units.
- Google Traffic.

TDMs are the traditional traffic data sources for transportation conformity, SIP, and National Air Quality Act (NEPA) air quality analyses. HPMS is a national data set used by the FHWA to support decisions on the physical condition, safety, service, efficiency of the national highway system (NHS), and federal highway funding, but is also used by organizations such as the EPA, MPOs, and transportation researchers. STARS-II data expand upon the data collected in Texas for the HPMS. The data are used to meet FHWA reporting requirements and for validation of TDM. NPMRDS and INRIX provide traffic data derived from vehicle probe-based data collected from mobile phones, vehicles, and portable navigation devices. Each of these data sources is presented in Figure 10 and described in the following sections.
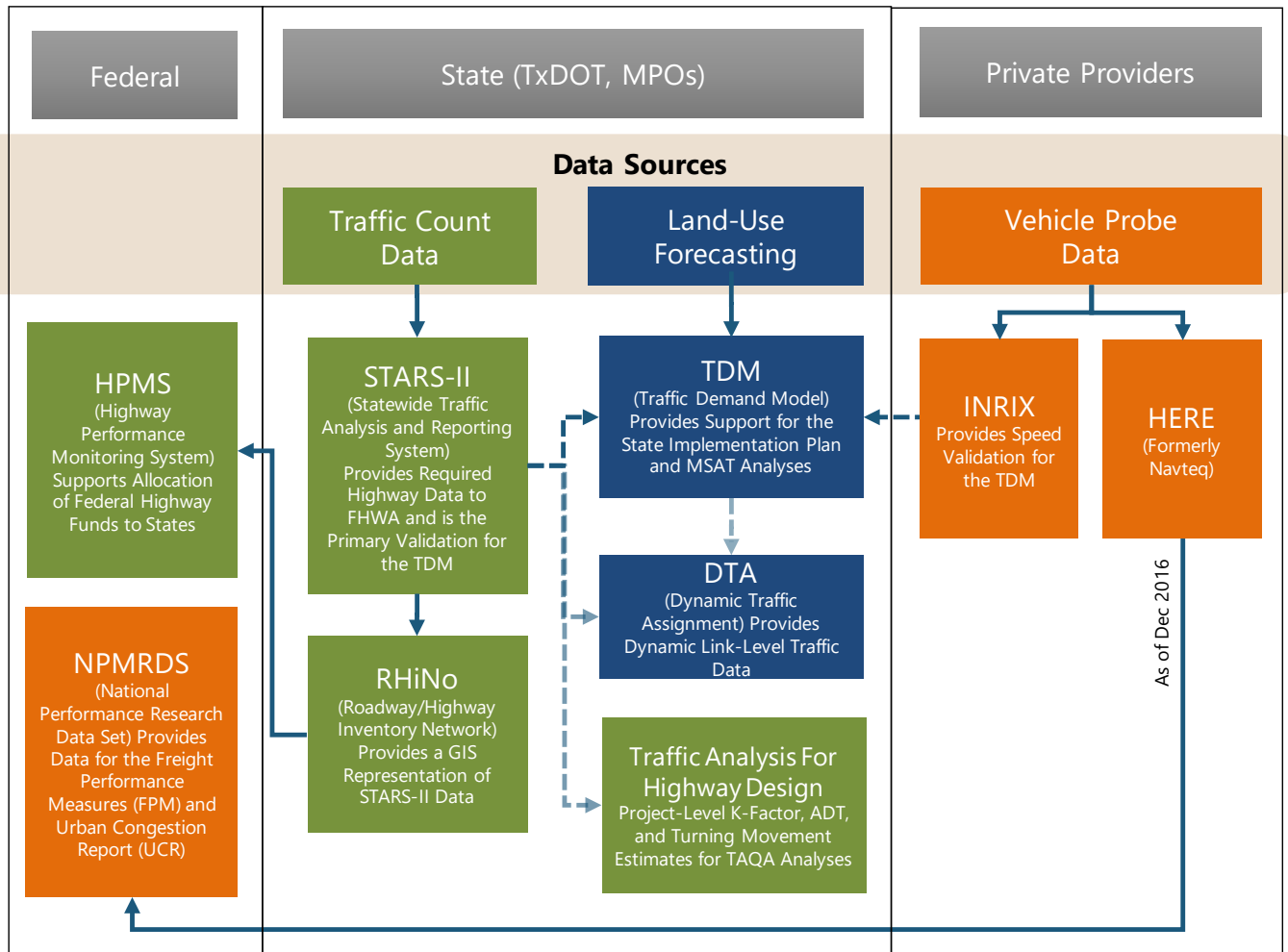
Figure 10. Major Traffic Data Sources and Uses.

TDM

Travel demand modeling is a travel forecasting method used to predict travel characteristics and usage of transport services based on alternative socioeconomic and land-use configurations for a modeled area. TDMs are used to evaluate transportation system alternatives that help transportation decision makers at the local and state levels improve the overall function of the transportation system. In Texas, TxDOT works with the MPOs in the development of their TDMs.

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The TDM traffic predictions are developed based on travels between traffic analysis zones (TAZs) for metropolitan areas with populations of over 200,000. The TDM uses TAZs, zone centroids, and centroid connectors developed by TxDOT's Transportation Planning and Programming Division (TPP), and the link-level data provided by the appropriate MPO and TxDOT's district office for the respective areas. The variables used by the TDM include comprehensive travel survey data, U.S. Census data, current, and projected sociodemographic data, existing and projected transportation system data, and current traffic data.

The TDM is validated by comparison of TDM-predicted, base-year traffic to replicate observed traffic counts. The TDM is the typical source of traffic data used for NEPA mobile source air toxics and regional emissions analyses. Available traffic data for NEPA mobile source air toxics analyses are limited to the analysis years provided by the MPO. Use of TDM data requires coordination between TxDOT, the MPO, and the user to obtain the data. Generally, all modeled links within the metropolitan area are included in the data set. User must determine the appropriate links for a particular project. The traffic output of model includes volume, speed, travel time, etc. for peak, off-peak hours.

HPMS

The HPMS is a national level highway information system that includes data on the extent, condition, performance, use, and operating characteristics of the nation's highways. The HPMS contains administrative and extent-of-system information on all public roads. Information on other characteristics is represented in HPMS as a mix of universe and sample data for arterial and collector functional systems (*69*).

The HPMS, initially implemented in 1978, is used to serve the data and informational needs of the FHWA. HPMS is a federally mandated program used by FHWA to provide data to Congress on the nation's streets and highways. Congress uses the data for allocation of funds to states. HPMS is a cooperative effort among state DOTs, local governments, and MPOs to assemble and report the necessary information. Every state collects, maintains, and reports certain data to the FHWA each year according to the methods prescribed in the HPMS Field Manual for the continuing analytical and statistical database (*70*).

TxDOT district offices collect, update, and submit the required information for roadways within their districts to TxDOT's TPP. The data are collected between September 1 and December 31 each year and are submitted to TPP by December 31 (*71*). TxDOT prepares an annual report to FHWA on or before June 15th each year in accordance with FHWA's HPMS Field Manual (*72*).

STARS-II

TxDOT's STARS-II comprises a statewide database of traffic activity and a web-based GIS interface that can be used to search for and download traffic count data. STARS-II addresses the federal requirement that all states implement a traffic monitoring system (TMS) for highways and transportation facilities and equipment (23 CFR 500 part B) and the mandate that states must report comprehensive and standardized traffic information to the HPMS.

STARS II supports a broader range of traffic measurements, at increased spatial and temporal resolutions than are available within the federal HPMS. The STARS-II data cover on- and off-

system roadways within Texas. Traffic data are collected at approximately 362 permanent count locations plus many short-term locations that are strategically distributed across the state. Temporary locations are used within a dynamic sampling plan that covers approximately 75,000 to 80,000 locations annually. Urban areas are monitored on a five-year rotating cycle using saturation counts. Manual traffic counts at over 700 locations are collected annually statewide, including at the Texas-Mexico border bridges. TPP is the operator for collection, analysis, and reporting of STARS II traffic data.

The program collects traffic count data in the form of traffic volumes, traffic volumes vehicle classification, vehicle speed, and vehicle weight. The results of these traffic count operations are stored in STARS-II database where the data are validated, analyzed, and made available for decision support.

Traffic Analysis for Highway Design

The *Traffic Analysis for Highway Design Memorandum* is prepared by TxDOT-TPP and includes project-level information that is typically used for NEPA environmental impact studies for noise, Traffic Air Quality Analysis, and particulate matter hot-spot analysis. The traffic data are based on STARS-II data, project-specific traffic counts, and/or professional judgement. The *Traffic Analysis for Highway Design* report typically includes the Annual Average Daily Traffic (AADT), K-Factor, and the directional distribution related to peak Average Daily Traffic (ADT) distributions (the 30th highest hourly volume) as well as turning movement diagrams illustrating the 20-year, and 30-year design period traffic projections. The project-level turning movement diagrams provide a summary of base year and forecasted year node-to-node turning movement for each intersection in the project area. This memorandum is generated by TPP's corridor analyst on request.

NPMRDS

NPMRDS is a vehicle probe-based travel time data set acquired by the FHWA to support its Freight Performance Measures[1] and Urban Congestion Report[2] programs. Probe data for passenger vehicles are obtained from several sources including mobile phones, vehicles, and portable navigation devices. Freight data are obtained from the American Transportation Research Institute leveraging embedded fleet systems.

NPMRDS consists of average travel times reported every five minutes on the NHS as defined in Moving Ahead for Progress in the 21st Century Act[3] and on a 5-mile radius of arterials at border crossings. It is monthly archived data. While the data are primarily for FHWA's use, FHWA is making the data available to states and MPOs, as well as to the Canadian and Mexican national governments, border provinces, and states for no charge. The data are used for performance

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[1] Freight Performance Measures help to identify needed transportation improvements and monitor their effectiveness and serve as indicators of economic health and traffic congestion https://ops.fhwa.dot.gov/freight/freight_analysis/perform_meas/#fhwa.

[2] The Urban Congestion Report is a quarterly snapshot of traffic congestion and reliability trends at the national and city level, developed using archived traffic operations data.

[3] Moving Ahead for Progress in the 21st Century Act authorizes funds for Federal-aid highways, highway safety programs, transit programs, and for other purposes; and expands the NHS to incorporate principal arterials not previously included. https://www.fhwa.dot.gov/map21/summaryinfo.cfm.

measures and to help grow the use and application of performance measures more locally and consistently.

The NPMRDS data set includes a static file, a monthly data file, and a shape file of the NHS. The *static file* provides the roadway information such as the industry standard roadway segment ID (standardized Traffic Message Channel location code), county, state, distance (length of TMC in miles), road number, road name, latitude, longitude, and road direction. The static file does not change every month and is updated only as needed to reflect the current roadway system. The *data file* is a .CSV file that includes the TMC code, date, epoch in 5-minute increments over a 24-hour period (0-287), travel time for all vehicles (seconds), travel time for passenger vehicles (seconds), and travel time for freight vehicles (seconds). The *shape file* includes the NHS map with the TMC codes and attributes such as: street name, functional class, travel direction, a controlled access flag, and ramp identifiers. Similar to the static file, the shape files do not change every month and are updated only as needed to reflect the current roadway system.

INRIX

INRIX, Inc. (*73*) is a private, subscription-based or fee-based service provider of crowd-sourced real-time traffic data. As of June 2016, INRIX data contain speed and location data from over 300 million real-time anonymous mobile phones, connected cars, trucks, delivery vans, and other fleet vehicles equipped with GPS locator devices. The data collected are processed in real-time 24-hours a day, creating traffic speed information for major freeways, highways, and arterials across North America (United States, Canada), as well as much of Europe, South America, and Africa. The information collected and analyzed includes historical GPS data and features historical data availability for nearly three years up to the previous day.

INRIX also provides on-demand, cloud-based analytics that use the traffic data to help public agencies and consultants monitor, measure, and manage the performance of road networks. INRIX data are referenced to the roadway database using Traffic Message Channel standardized location coding. Data are available at a temporal resolution of 1, 5, 15, 30, and 60 minutes and includes:

- Volume: day of week and time of day estimated traffic counts for freeways and arterials.
- Speed: historic speed and travel time data in an archival or profile format.
- Trips: Geospatial data for population origin and destination zones, diversion routes during peak time and incidents, corridor usage, etc.

INRIX also keeps a database of variables that affect traffic, including weather forecasts, special events, school schedules, and road construction. These variables are combined with the real-time probe data for major mobile operating system applications such as INRIX Traffic and INRIX ParkMe.

TxDOT Sensors

TxDOT districts use radar sensors installed on local highways to measure traffic characteristics. These units are mounted alongside highways and are typically spaced one mile apart. Each detector records volume, speed, and occupancy by lane and at 20-second intervals. Information

from the vehicle detection units is transmitted to districts, which typically monitor changes in traffic operating speeds to identify locations of any potential incidents that may restrict traffic flow. The detector data used to be archived by detector location. However, in September 2014, districts converted their advanced traffic management system to a statewide monitoring system, Lonestar. This software allows for cooperation between districts and standardizes all devices across the state. Districts have access to raw sensor data in their respective jurisdictions and processed/archived data through Lonestar and use it for performance monitoring. For instance, Dallas has been using the detector data to derive performance measures to describe traffic congestion and travel reliability of a highway. These data are also used in the national Urban Mobility Report prepared by TTI and the Urban Congestion Reports produced quarterly by FHWA. Prior to these calculations, the data are processed through several quality checks to filter out potential outliers in the data. These measures include:

- Congestion duration.[4] The congestion duration is the average number of congested hours on instrumented road segments during the three-hour peak period. For this measure:
  - *Total congestion* occurs when link speeds are less than 50 mph.
  - *Severe congestion* occurs when the average speed on any link or segment falls below 30 mph.
- Travel time index.[5] The travel time index is the ratio of the average peak-period travel time as compared to a free-flow travel time. For example, a value of 1.20 means that average peak travel times are 20 percent longer than free-flow travel times. In this report, the AM peak period is 6:00 a.m. to 9:00 a.m., and the PM peak period is 4:00 p.m. to 7:00 p.m. on non-holiday weekdays. Averages across road sections and time periods are weighted by vehicle miles traveled.
- Planning time index.[6] The planning time index is a ratio of the total time needed to ensure 95 percent on-time arrival as compared to travel time at 50 mph. For example, a value of 1.40 means that a traveler should budget an additional 40 percent more time (e.g., an eight-minute buffer) for a 20-minute trip to ensure 95 percent on-time arrival.

Google Traffic Maps

Google traffic data are continuously acquired by Google if a user has turned on the location service on the smartphone (does not matter if they have Google Maps open). Google combines and stores all the data coming in from all vehicles traveling on the roadway network. This information is displayed in real-time when user seeks for travel time information from Google maps. The Google Maps Directions API allows public users to query the database at any interval (seconds, minutes) and the returned results contains the time it will take to travel between the two points at a particular time and these data can be stored locally in the database. Google Maps does not support viewing or accessing historical traffic data (*74*).

Table 9 summarizes information about the above traffic data sources.

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[4] Congestion duration is reported for non-holiday weekday AM (6:00 a.m.–9:00 a.m.), weekday PM (3:00 p.m.–7:00 p.m.), and weekend mid-day (9:00 a.m.–3:00 p.m.).

[5] The travel time index assumes 50 mph as the free-flow speed for each road section.

[6] The planning time index is computed for non-holiday weekdays AM peak period (6:00 a.m.–9:00 a.m.), PM peak period (3:00 p.m.–7:00 p.m.), and weekend mid-day (9:00 a.m.–3:00 p.m.).

Table 9. Available Traffic Data Sources for Emission Analysis.

Data Source	Traffic Data Source	Data Resolution	Data Type(s)	Processes Conducted on Data	Issues Regarding Data Extraction and Usage
TDM	Traffic is developed based travel between TAZs for metropolitan areas with populations of over 200,000. These data are validated using TxDOT's HPMS traffic count data.	Link-level data within the metropolitan area. Model uses TAZs, zone centroids, and centroid connectors developed by TPP, the MPO, and TxDOT's district office.	CSV file with speed, capacity, area type, functional class, and facility class, etc.	The TDM is validated by comparison of TDM-predicted, base-year traffic to replicate observed traffic counts. Average weekday traffic with peak hour and directional percentages or directional peak-hour volumes for the estimated time of project completion (ETC), ETC + 10 years, and ETC + 20 years.	Year of available traffic data is limited to the years provided by the MPO. Requires coordination between TxDOT, the MPO, and the user. Generally, all modeled links are included in the data set. Users must determine the appropriate links for a particular project.
HPMS	A federal database of standardized traffic data provided by the states.	Data locations references are related to the GIS data set through linear referencing.	Geospatial data of highway systems, geographic boundaries, roadway attributes, and metadata that.		Data prepared by TxDOT for FHWA.
STARS-II	362 permanent pneumatic tube traffic counters and many short-term locations and collects traffic volumes, traffic volumes classified by vehicle type, vehicle speed, vehicle weight.	Data locations references are by the Geospatial Roadway Inventory Database system.	Data include volume, vehicle classification, speed, and weight-in-motion. Data are available in detail reports or in listing reports and may be downloaded as CSV, PDF, Excel, or TIFF files.	The data are validated and analyzed by TPP prior to release.	Data are available free-of-charge to the public through a web browser.

Data Source	Traffic Data Source	Data Resolution	Data Type(s)	Processes Conducted on Data	Issues Regarding Data Extraction and Usage
Traffic Analysis for Highway Design	TDM, STARS-II, or project-specific traffic counts.	Project link-level.	Project-level ADT, K-factor, directional distribution, ADT percentages and design hourly volumes of light, medium, and heavy-duty vehicles.	ADT is projected for the ETC, ETC + 20 years, and ETC + 30 years.	Provided by TPP. If data are generated outside of TPP, TPP is required to review and approve the traffic data.
NPMRDS	Passenger probe data obtained from phones, vehicles, and portable navigation devices, and from freight probe data collected by American Transportation Research Institute and provided by HERE.	5-minute data.	TMC shape files.	Passenger probe data and freight probe data are provided as vehicle data, truck data, or both.	Federal Data.
INRIX	Real-time anonymous mobile phones, connected cars, trucks, delivery vans, and other fleet vehicles equipped with GPS locator devices.	1, 5, 15, 30, and 60-minute temporal resolution at 100 meter granularity.	Data are provided as raw data, processed data, and/or as shape files. Roadway locations are referenced to the TMC.	Data are processed to provide travel time, time-cost delays, trends maps and charts, bottleneck and incident data, and can provided the underlying anonymized historical data for download.	Privately owned data provided. Data use the TMC Roadway location reference system.

Data Source	Traffic Data Source	Data Resolution	Data Type(s)	Processes Conducted on Data	Issues Regarding Data Extraction and Usage
TxDOT Vehicle detection Units	Installed on local highways and are used to measure traffic speeds and traffic volumes.	20 second internal volume, speed, and occupancy by lane.	Data are provided as raw data, processed data, and/or as shape files. Detection unit locations is referenced.	Data are processed to develop performance measures are used to describe traffic congestion and travel reliability of a highway.	Provided by TxDOT districts.
Google Traffic Map	Traffic data are acquired by the Google when smartphone users turn on their Google Maps app with GPS location enabled. For real-time data can be accessed and stored in the database. Historic data are unavailable.	User-defined intervals.	Data are downloaded as travel time from point A to B.	Data can be processed to develop link level speed.	Data cannot be used for commercial purposes.

MODELING AND FIELD STUDIES PERFORMED

TRAFFIC ACTIVITY MODELING

Overview

For achieving project objectives, researchers used a simulation-based modeling approach to examine the impacts of ramp metering on traffic operations and emissions in two DFW area freeway corridors, namely US 75 and I-20. In the first stage of traffic activity modeling process, researchers used DynusT, a regional DFW mesoscopic model, to analyze congestion at the system and corridor levels. In the second stage of traffic activity modeling, they extracted subarea models and converted them to microscopic format to conduct focused analysis at localized levels. In the third stage, they used outputs from mesoscopic and microscopic simulations to evaluate impacts of ramp metering on air quality at regional and local levels. The DFW DynusT mesoscopic model was originally developed as part of TxDOT project entitled "Strategies for Managing Freight Traffic through Urban Areas" in 2017. The model is a direct conversion from NCTCOG official regional TDM to a simulation-based mesoscopic model and is calibrated to 2015 traffic conditions using existing data. Figure 11 depicts the traffic activity modeling process used in this project.
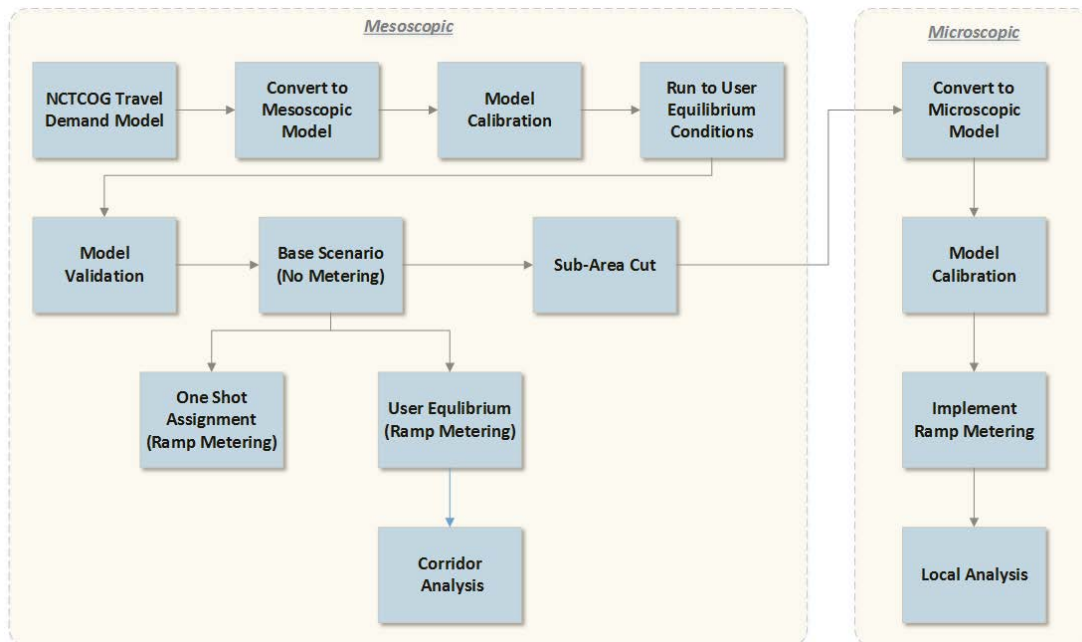
Figure 11. Modeling Process.

Researchers selected corridors for mesoscopic-level modeling (Meso_Limits) from an initial list of corridors identified by members of the TxDOT team. Figure 12 shows locations of the corridors. This figure also identifies some corridors that could not be used in this project because of ongoing or about-to-start construction projects. From a traffic congestion perspective, I-35W in Fort Worth could be a good candidate. However, team's assessment was that it might be difficult to install ramp-metering hardware in this corridor due to high walls and concrete from

right of way to right of way on both sides. Sections of US 75 in Dallas, especially in the downtown area, also have similar issues.
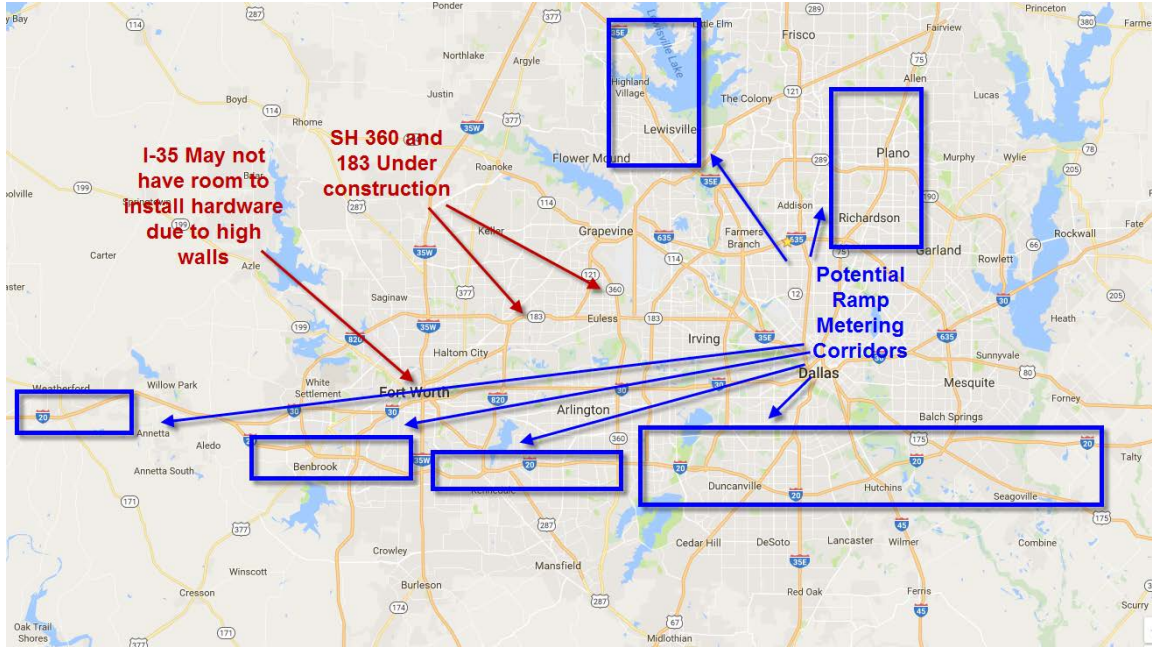
Figure 12. Initial List of Potential Ramp Metering Corridors Suggested by TxDOT Team.

To identify subarea cuts for microsimulation (Micro_Limits), researchers developed and examined heat maps using speed data from TxDOT radar sensor and INRIX speed data. Researchers concluded that data from both these sources could be used for identifying the times and locations of congestion in corridors of interest. However, probe-based speed data, such as INRIX, provide a better picture of segment speeds than point-based measurements from radar sensors, especially during stop-and-go conditions. Figure 13 and Figure 14 show heat maps for southbound US 75 and both directions of I-20. Researchers used these heat maps to identify sections of these corridors for simulation-based analysis, including durations of ramp metering.

The limits of US 75 corridor selected for mesoscopic analysis consists of southbound (inbound) flow direction extending from Sam Rayburn Tollway to I-635, which is approximately 17 miles long. A smaller subarea cut US 75 extending from Stacy Blvd to W Park Blvd (approximately 8 miles) in the southbound direction was selected for microsimulation. Ramp metering was implemented from 6:00 a.m. to 9:30 a.m. during the morning peak period while the afternoon peak period was modeled from 2:30 p.m. to 7:00 p.m. The I-20 corridor was modeled in both EB and WB directions, with the mesoscopic limits extending from US 377 (Benbrook Hwy) to I-45. The mesoscopic model is approximately 45 miles in length. A 9.5-mile subarea the I-20 extending from Matlock Rd. to Mountain Creek Pkwy was selected for microsimulation. In this corridor, ramp metering was implemented from 6:45 a.m. to 9:45 a.m. during morning rush hours while the afternoon peak periods were modeled from 3:15 p.m. to 7:00 p.m. Figure 15 shows limits (Meso_Limits and Micro_Limits) used for mesoscopic and microscopic simulations.

Figure 13. 2016 INRIX Speed Data for Southbound US 75.

Figure 14. 2016 INRIX Speed Data for I-20.

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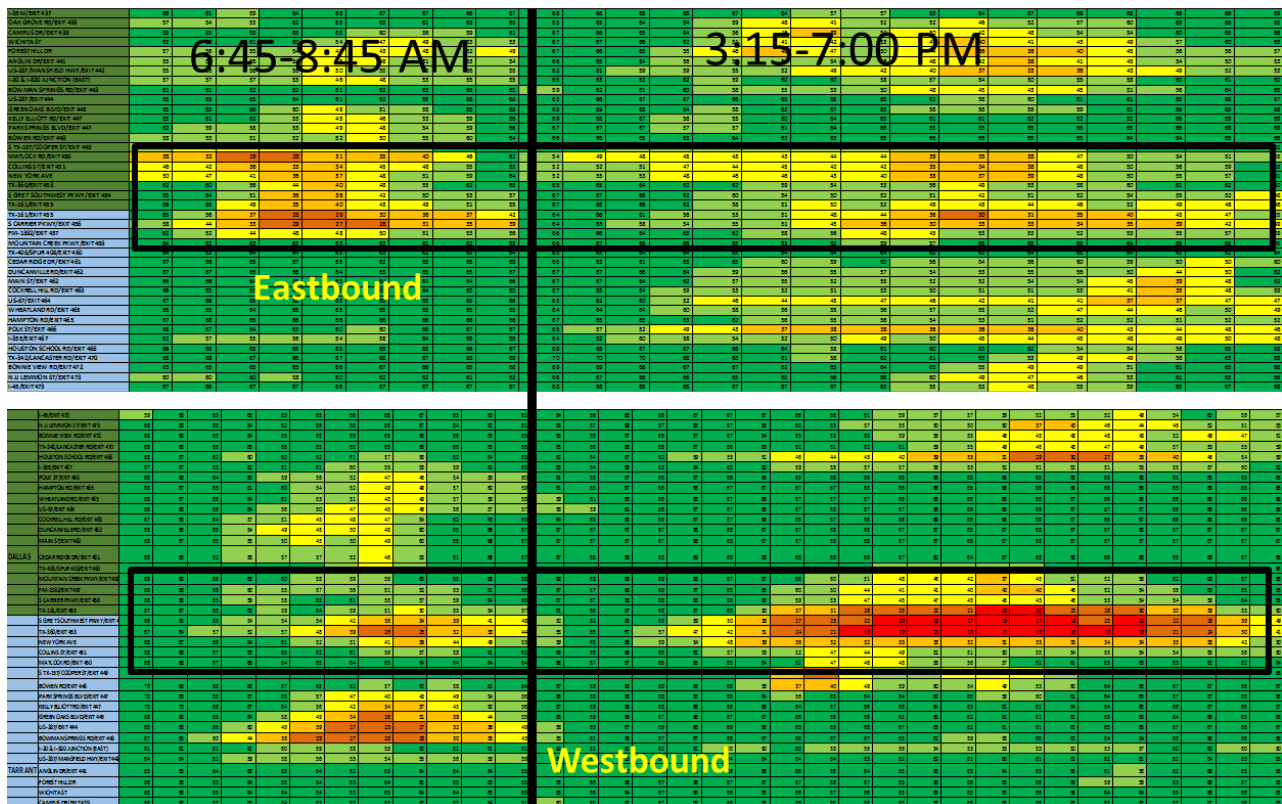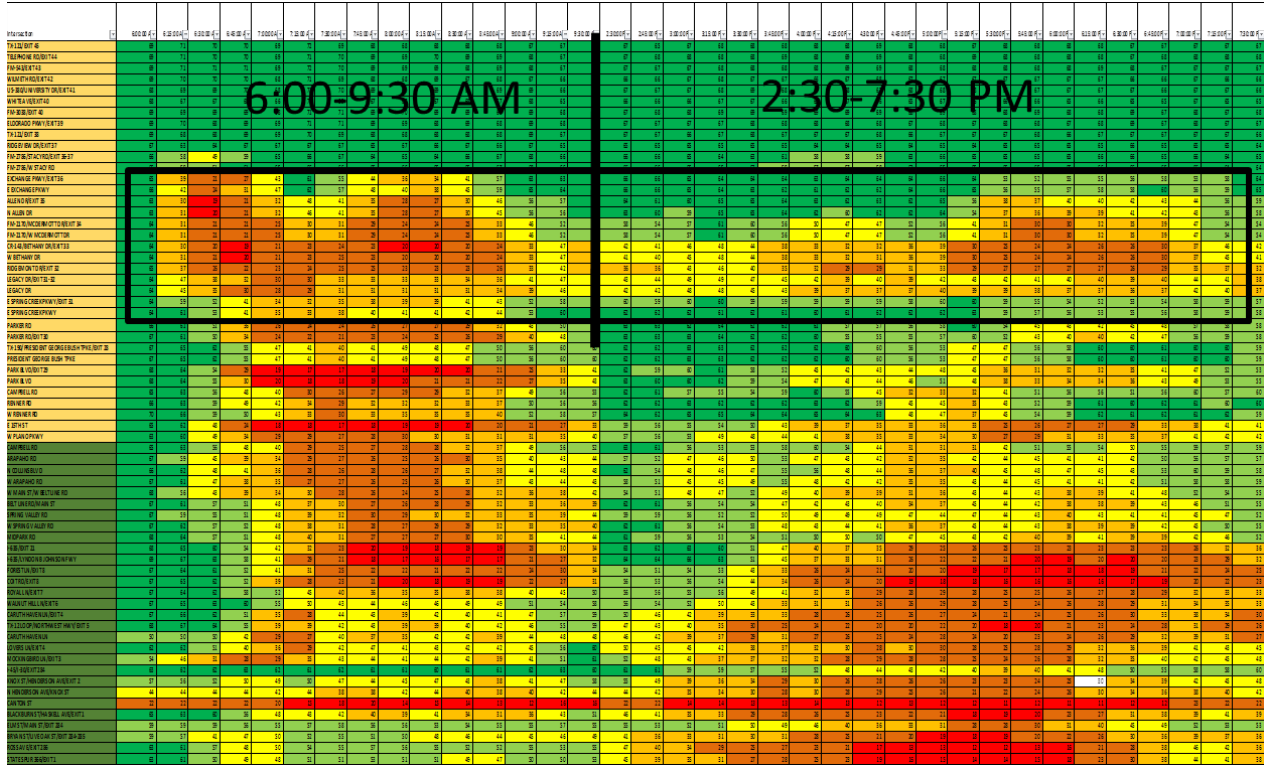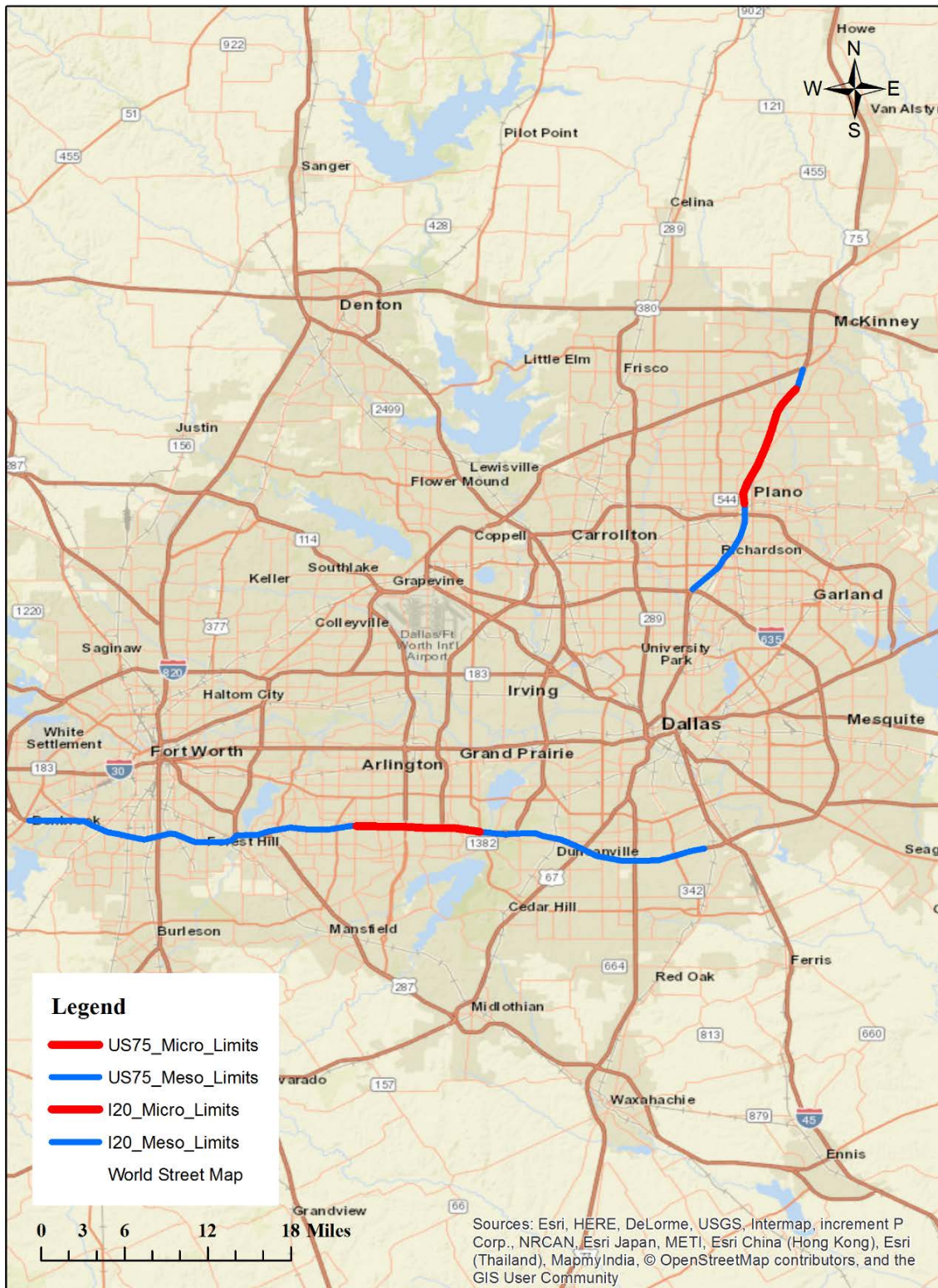
Figure 15. Modeled Project Limits.

The DynusT (mesoscopic) model includes the entire area represented by the NCTCOG Regional TDM and included the counties of Dallas, Denton, Rockwall, Collin, and Tarrant, the western

portion of Kaufman County, the eastern portion of Parker County, and the northern portion of Ellis and Johnson Counties. This roadway network consists of 60,951 links and 25,683 nodes and three distinct time periods (AM peak, PM peak, and off-peak) and includes both airport and truck components. The conversion process exported all information from TDM to DynusT. This information included link characteristics (including functional classifications), link lengths, node identifications,[7] link direction, street name, speed limit, roadway capacity/saturation flow, toll lanes and HOV lanes, X-Y node coordinates, and all zonal information. DynusT model includes all controlled intersections (3,962 traffic signals, 1133 four-way stop signs, 4725 two-way stop signs, and 102 yield signs) in the current NCTCOG model. The original DynusT model uses a default two-phase 90-second signal timing plan for all signalized intersections.

To create the base (no-metering scenario) for this research project, researchers updated signals timings for all interchanges along the two selected micro corridors and recalibrated the model using data form TxDOT's Automatic Traffic Recording Stations depicted in Figure 16.
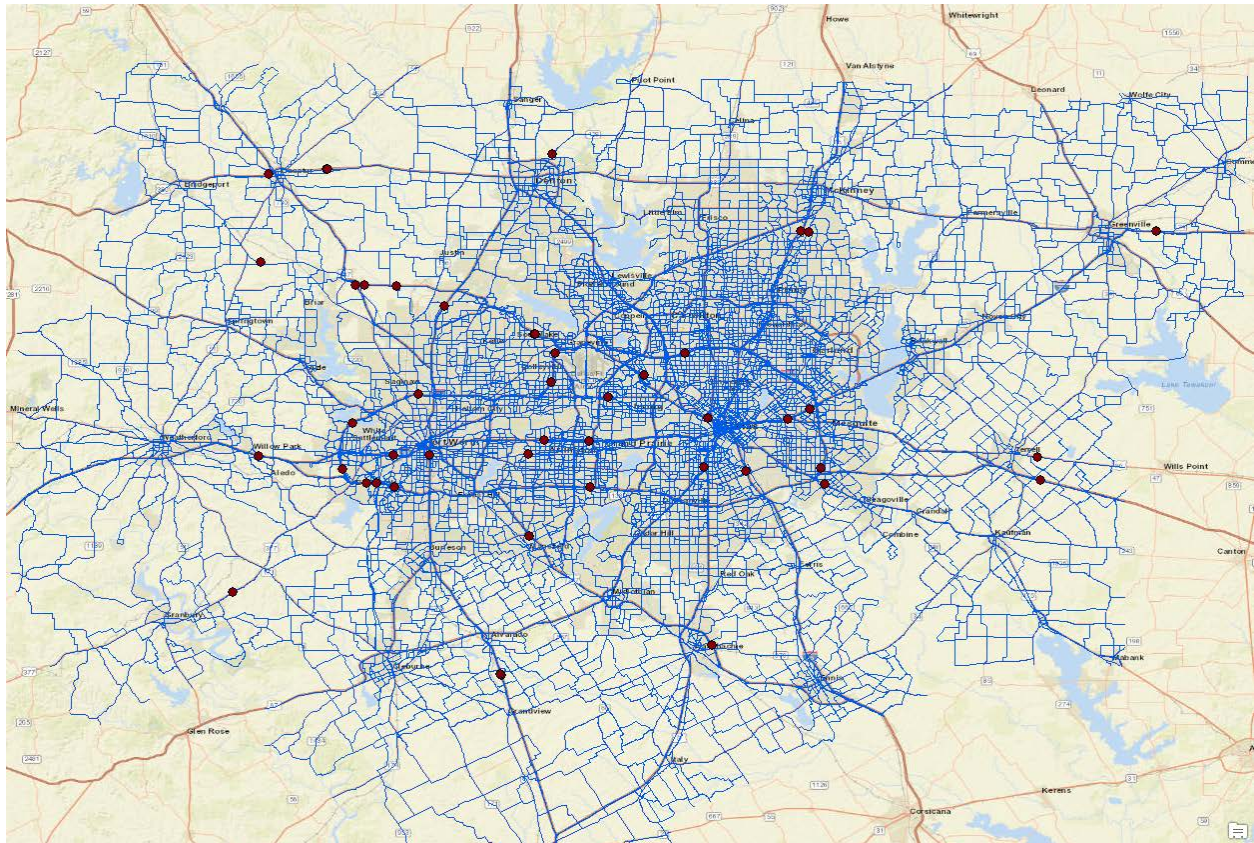
Figure 16. Automatic Traffic Recording Stations Locations.

Researchers also validated calibration results by comparing simulated speed data against speed data from the field as illustrated in Figure 17 for two locations on I-20. In this process, the based model was simulated for user equilibrium (UE) conditions.

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[7] Node identification refers to the beginning and end points used to define a link.
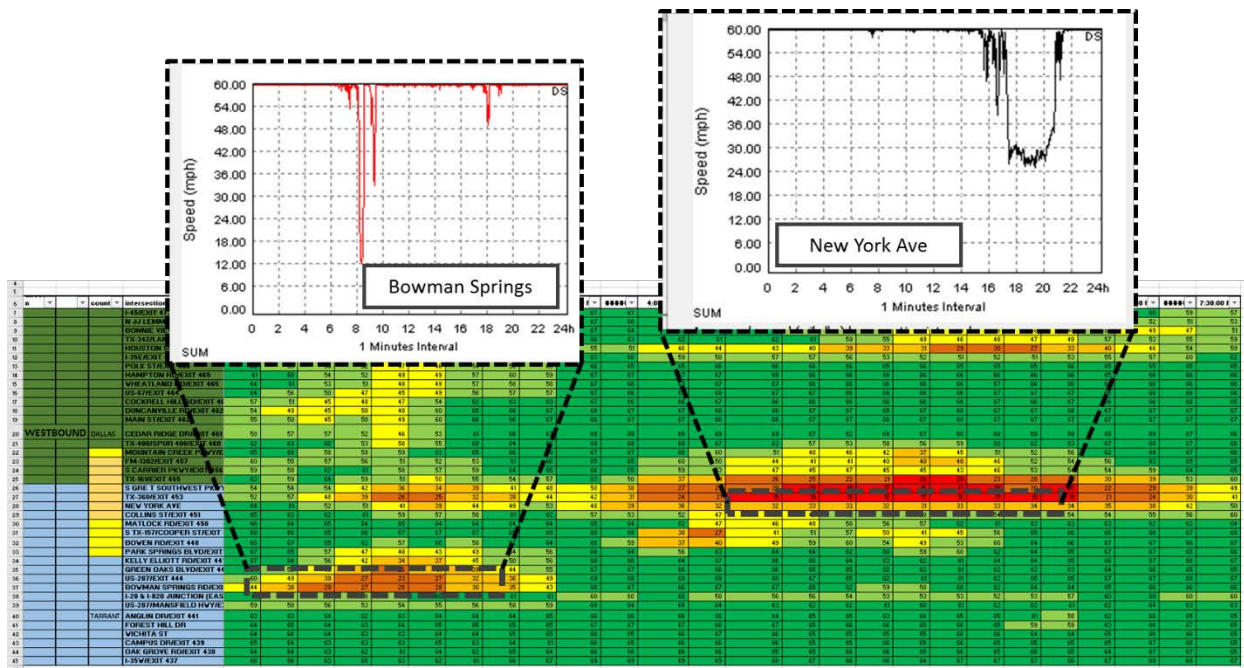
Figure 17. Speed Validation—I-20.

Fifteen-minute link speeds and link volumes from the base model provide a basis for comparison to ramp metered scenarios. Two additional scenarios were developed with ramp metering employed. The first scenario was run as an initial test to determine how vehicles react to ramp meters immediately after implementation. This assignment of vehicle paths is known as one-shot assignment. One-shot simulation represents the next day after implementation where drivers will still take their normal routes to work. The second scenario is termed UE where the model is run over multiple iterations, where vehicles search for new and updated time-dependent shortest paths. UE signifies several weeks of drivers learning and updating their routes from origin to destination.

Microscopic Model Development

Once the base mesoscopic model reached equilibrium conditions, a subarea of the project limits for each corridor was created from the regional network. After the subarea process was completed, the mesoscopic models were converted to a microscopic counterpart using a proprietary[8] conversion tool. The tool converts over all links, nodes, and most importantly, time dependent paths and flows. The microscopic models were cut out to include the freeway corridor, adjacent frontage roads, and signalized interchanges. During the subarea process, all links, nodes, and zones outside the boundary area are discarded and the zonal definitions are renumbered. All paths and flows are truncated at the boundary lines. Each model was prepared to provide for a 24-hour simulation of traffic flow between all origins and destinations. Once converted to a micromodel, additional manual cleanup is generally necessary to simulate realistic conditions at the microlevel. Manual cleanup involved adding or tweaking roadway geometry, speed limits, speed reduction areas, lane changing distances, and right-of-way constraints.

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[8] DynusT-VISSIM Converter developed and maintained by TTI.

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Figure 18 and Figure 19 illustrate the project limits of US 75 and I-20 microscopic models. As shown in these figures, the US 75 microscopic model contains six signalized interchanges and 10 metered on-ramps. The limits of this model are slightly larger than originally planned in that it contains an extra signalized interchange (15th Street) and two additional metered ramps located at the south end. The extension was adopted to simplify conversion of path and flows from mesoscopic model. The I-20 model contains eight signalized interchanges and seven metered on-ramps in each flow direction, with a total of 15 metered ramps in the corridor. I-20 also has two major multilevel unsignalized interchanges (SH 360 and Lake Ridge Pkwy) and associated freeway-to-freeway entrance ramps. These entrance ramps, especially those feeding traffic from SH 360 to I-20 carry significant traffic volume during peak periods. Freeway-to-freeway ramps from I-20 to SH 360 are also a source of bottleneck for I-20 traffic. Researchers exerted considerable effort to ensure that the models exhibited realistic vehicle behavior. This subtask consisted of several iterations of the following process for each of the two models:

1. Run the model.
2. Observe animation and identify issues.
3. Fix identified issue(s) and repeat these steps.

This process allowed researchers to identify and correct several issues related to vehicle speed selection, path selection, weaving, and ramp merge.
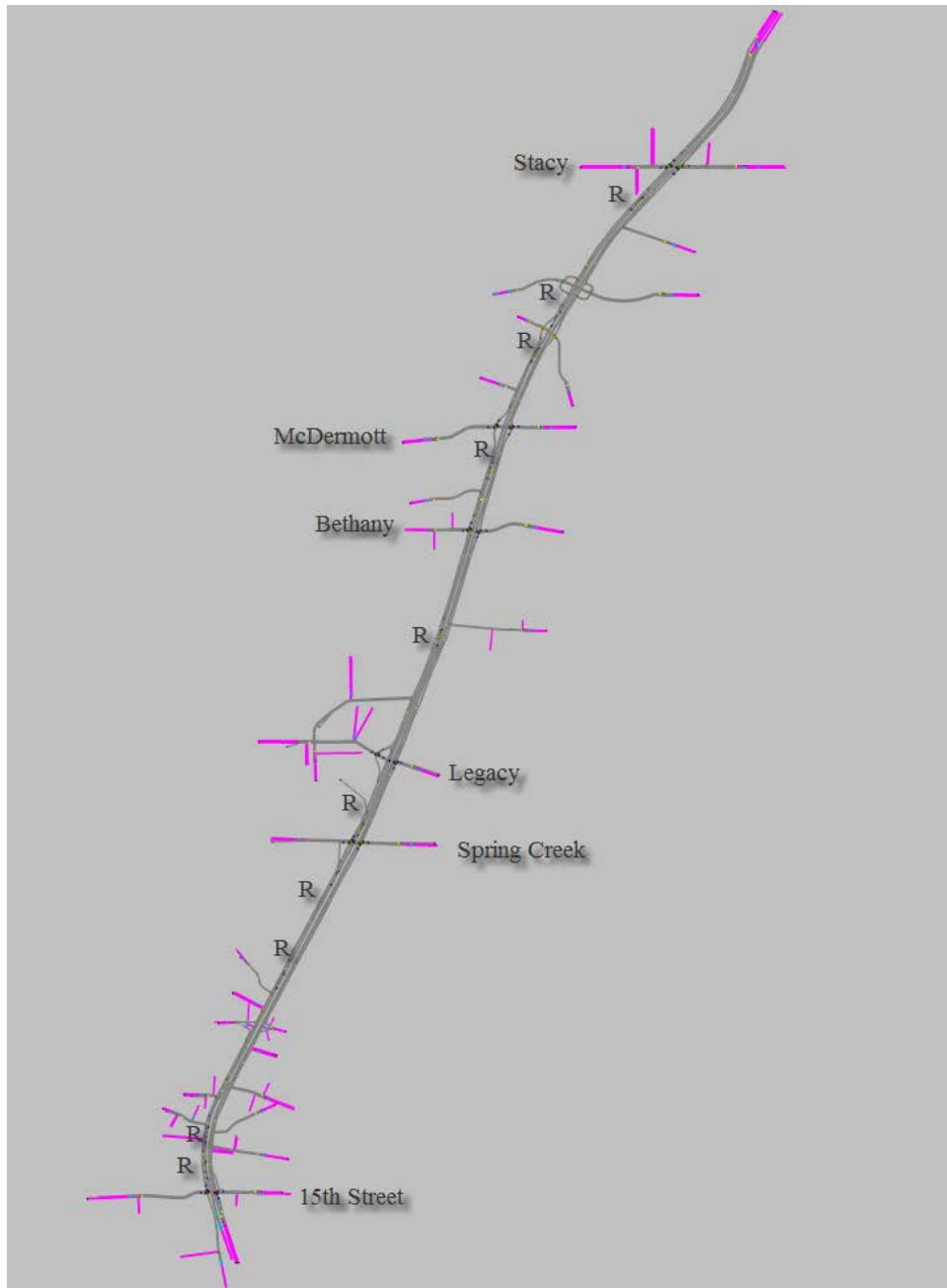
Figure 18. US 75 Microscopic Simulation Model.
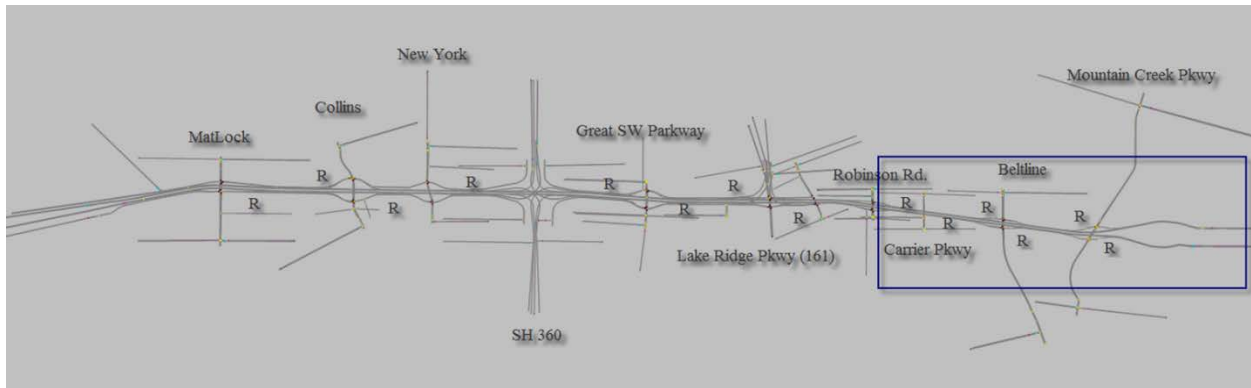
Figure 19. I–20 Microscopic Simulation Model.

In addition to clean-up and refinement of the basic models, researchers added two types of signal control: signal control at diamond interchanges and ramp control at metered ramps.

Diamond Interchanges

At researchers' request, NCTCOG obtained timing sheets for all relevant signalized interchanges from cities along the selected corridors. Each timing sheet contains ring-barrier structure, basic timing parameters, coordination plans, and time-of-day schedules. However, timing sheets do not include one critical piece of information required for implementation. This piece of information is the phase-to-direction mapping. Without this information, it was not possible to implement signal control into a simulation model. Thus, at the onset of this task, researchers contacted cities to obtain the missing information. In a few cases, additional information was needed. This includes a case where a single controller is being used to provide coordinated control at the interchange and an adjacent signalized intersection. Cities contacted by researchers included Arlington, Grand Prairie, Allen, and Plano. The additional information provided by these cities was in various formats such as screens from an optimization software, standard template, and location specific mapping. Once researchers received all required information, they created microsimulation timing plans for all interchanges. Figure 20 and Figure 21 illustrate data coding for implementing timing plans in VISSIM.

Figure 20. Basic Timing Plan.
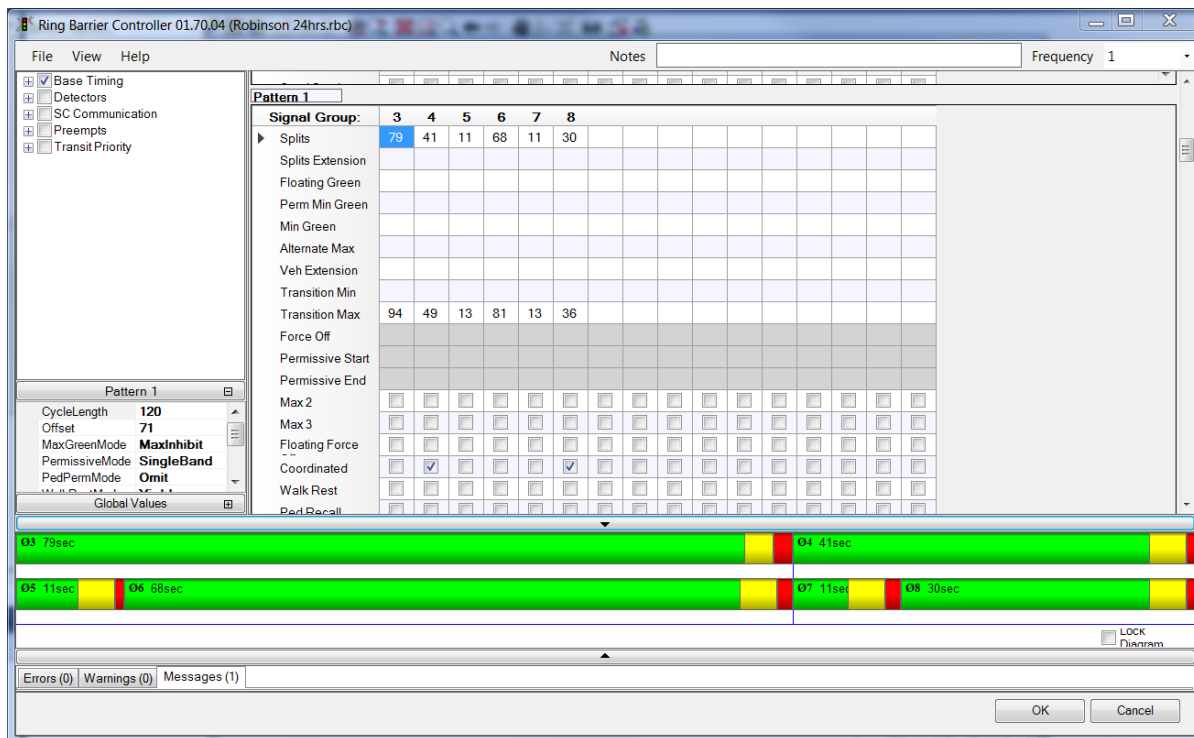
Figure 21. Example of Pattern (Coordination) Data.

Ramp Meters

For implementing ramp metering, researchers used the built-in VAP feature in VISSIM. To use this feature, a user develops a text file containing signal control logic and requests VISSIM to use logic in the specified file instead of built-in controller logic. Researchers used a ramp control VAP file to implement the three metering scenarios: no metering, strict metering, and metering with queue flush.

Researchers simulated three scenarios in microsimulation:

- No metering.
- Strict metering.
- Metering with queue flush. In this scenario, every time a queue was detected at an upstream queue detector, the meter changed the signal indication to green to clear the queue. Metering with queue flush prevents ramp queues from blocking upstream intersections.

For each scenario, researchers simulated five replications with different random seeds. These replications emulate day-to-day variations in traffic flow. This option resulted in 15 runs for each of the two corridors. For analyzing each scenario, researchers averaged results from all replications related to it.

Simulation and Data Collection

To allow comparison between scenarios, researchers requested VISSIM to save the following outputs:

- 15-minute link data, including speeds and volumes. These data are similar to data produced by the mesoscopic model (DynusT).
- Queue lengths at entrance ramp merge points and ramp meters.
- Freeway speeds upstream and downstream of entrance ramps.
- Duration each ramp was under flush mode in the metering-with-queue-flush scenario.

Researchers executed all 15 simulation runs (3 scenarios and 5 replications for each), summarized the results for the three scenarios, and examined the results. This examination identified the need for adjustments in VISSIM simulations models for both corridors. Researchers re-ran all 15 scenarios after making the following adjustments:

- Adjustments to vehicle merge areas at two on-ramps in the US 75 model to correct unrealistic merge behavior.
- Adjustments to vehicle merge areas at two on-ramps in the I-20 model to correct unrealistic merge behavior.
- Removal of Mount Creek Parkway ramp meters in both directions. The meter in the WB direction was removed because simulated ramp demand from this sign-controller interchange was much higher than the capacity of a single-lane meter. In the EB direction, the meter was removed because the stop-and-go operation was observed to naturally metering traffic at this ramp.

EMISSIONS MODELING

Approach

A modeling approach combining mesoscopic and microscopic traffic simulation with emission rates from EPA's newest emission model, MOVES, was developed and applied to estimate the vehicle emissions impacts of ramp metering for the selected case studies. Figure 22 summarizes the modeling steps in the flowchart. In addition to the emissions modeling analysis, researchers collected and analyzed a sample of 1 Hz vehicle activity data for a sample of on-ramps in Houston before and after ramp metering was activated on them.

The approach shown in encompasses two distinct analytical approaches to estimate the emissions impact of ramp metering: regional and corridor level. The analysis of the regional impacts of ramp metering focuses not just on the corridor(s) in which ramp metering is deployed, but rather uses mesoscopic modeling results and DTA to assess the impacts on the broader traffic network including potential re-routing by some vehicles. This is achieved through including all the links that fall within the influence zone of the corridor. In this research, the influence zone was defined as a distance buffer around the corridor. Distance buffer sizes of 1, 2, 3, 4, and 5 miles were used to estimate the potential change in emissions because of ramp metering. The assessment of the corridor impacts, on the other hand, focuses only on the corridor(s) in which ramp metering is

deployed, including activity changes on the ramps and main lanes. Two different corridor-level analyses were conducted as follows:

- Link-based analysis based on the link-level traffic volume and speed outputs from mesoscopic model.
- Link-based analysis based on the link-level traffic volume and speed outputs from microsimulation.

The estimation of emissions from traffic activities requires knowledge of two main components: traffic activity and emission rates. Traffic activity is generally expressed as link-level volumes (expressed as VMT) and average speeds, and can be estimated using traffic simulation models such as VISSIM and DynusT. Similarly, emission rates are obtained using MOVES emissions model, based on regional or local specific information.
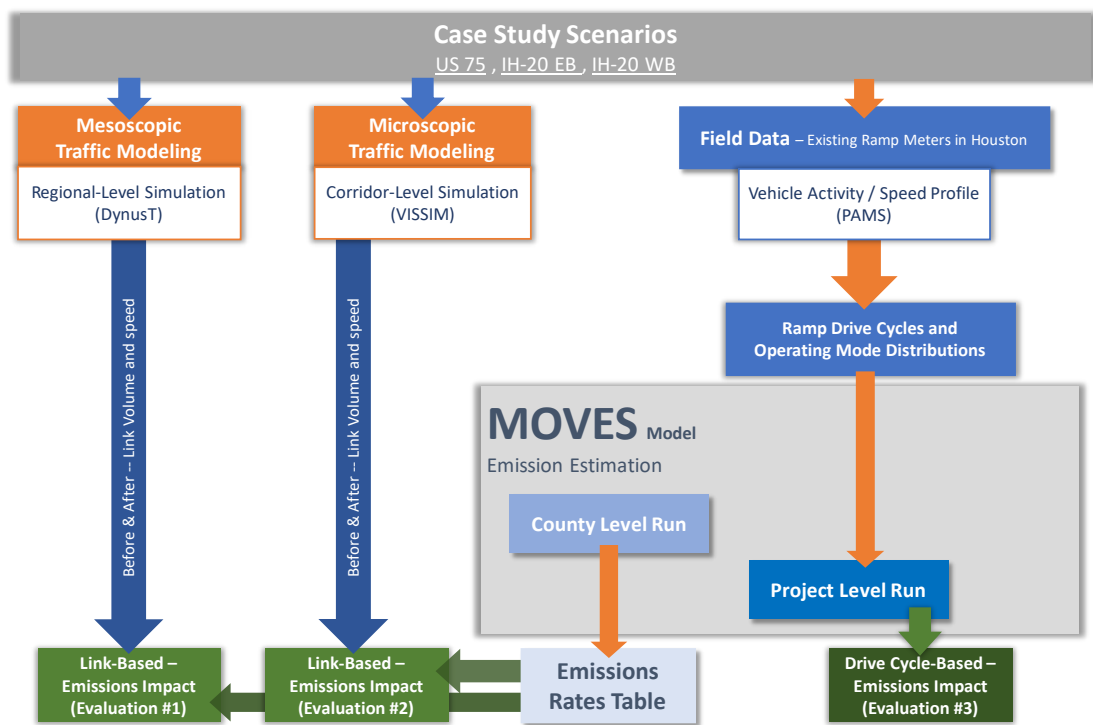
Figure 22. Emissions Analysis Framework for Ramp Metering.

Researchers used an integrated data analytics tool (Microsoft Power BI) to prepare and process the traffic and emission models' output, estimate emissions, analyze, and visualize the resulting estimates. Researchers automated all the steps from reading data to generating graphs and summary tables in Power BI with no manual intermediate steps. In addition to its data processing and analysis functions, the interactive visual dashboarding and mapping capabilities of Power BI enabled researchers to perform quality control, examine multiple scenarios, and isolate and evaluate the impacts of specific combinations of parameters. Researchers developed multiple data evaluation and visualization dashboard for this purpose. Figure 23 shows one of the dashboards developed by researchers. As shown in the figure, researchers could evaluate the emissions changes by corridor, vehicle type, road type, and the size of influence zone (i.e., buffer

size). This dashboard turned out to be a very useful tool and researchers decided to expand it to also analyze traffic activity data.
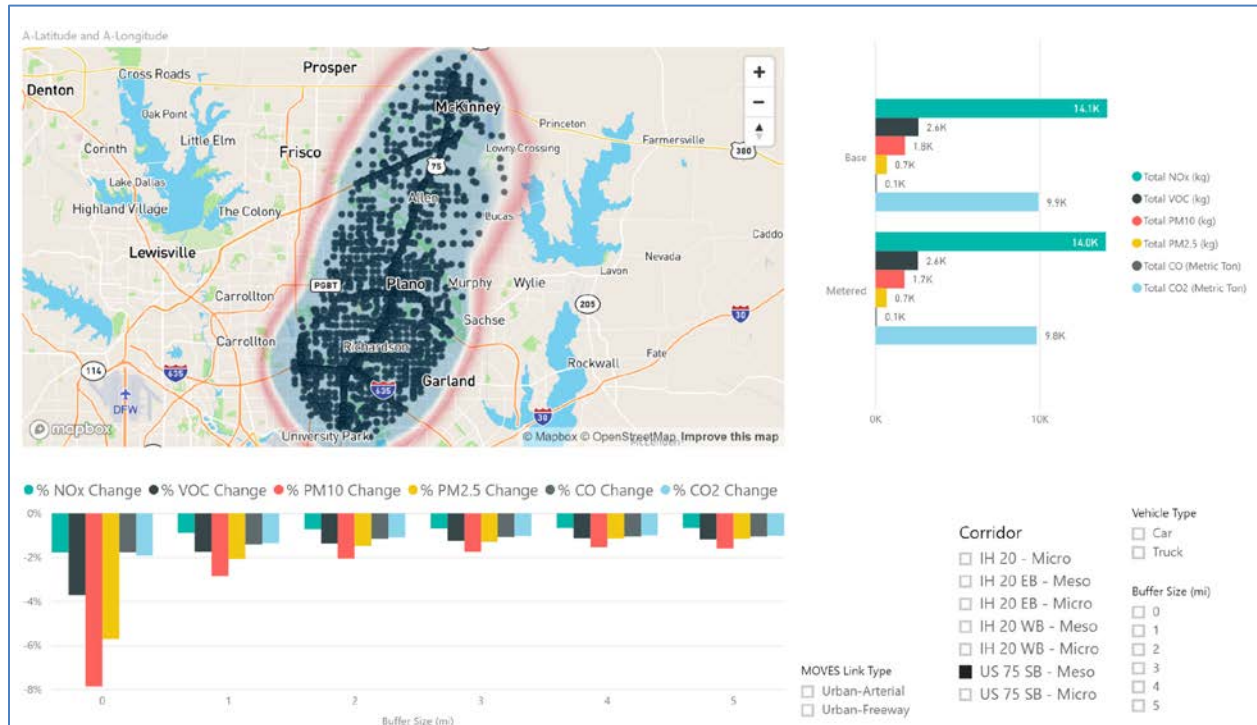
Figure 23. Screenshot of Interactive Dashboard; Summary Emissions for US 75.

Emission Rate Development

Researchers used the latest version of the MOVES model available at the time (MOVES 2014a) as the basis for the emissions analyses. Two types of emissions analyses were performed as part of this study:

- Link-based analysis: traffic activity information (i.e., VMT and speed) for each link were combined with speed-sensitive average emissions rates extracted from MOVES.
- Trajectory-based analysis, which includes drive cycle analysis: second-by-second vehicle speed data were translated into operating mode (opMode) bin distributions and were input into MOVES for a project-level analysis run. MOVES internally applies appropriate emission rates for each opMode bin and calculates the total emissions.

Although the estimation process is slightly different in these cases, off-model estimation for link-based versus in-model estimation for trajectory-based, the same local input parameters and assumptions are used in both approaches. In both cases, emissions are by vehicle type (cars and trucks) and roadway classification (freeway/highway and arterial). The pollutants that were included in the emissions analyses of this study include:

- NOx.
- VOCs.
- CO.

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- Particulate Matter (PM): 10 micrometers or less in diameter (PM10) and 2.5 micrometers or less in diameter (PM2.5).
- CO_2.

The MOVES model has 13 vehicle types; the traffic simulation used in this study uses a simplified vehicle classification (i.e., cars and trucks). A common solution for applying MOVES emission rates to simulation results is to develop composite emission rates from MOVES' 13 vehicle type using local fleet mix information. The following steps describe the process that researchers used to develop composite emissions rates.

Step 1—Develop MOVES County Data Set

To use MOVES for local emissions analysis, the users should input local information on vehicle types, age, fuel types, and other emissions parameters. Researchers used inputs and methodologies developed by TTI for TCEQ's SIP inventory analyses. Table 10 provides a summary of the County database (CDB) input tables used for this analysis.

Table 10. MOVES County Database Input Tables.

MOVES Input Table	Data Category	Notes
year	Time	Designates analysis year as a base year (base year means that local activity inputs are supplied rather than forecast by the model).
state	Geography	Identifies the state (Texas) for the analysis.
county	Geography/ Meteorology	Specifies the county, local altitude, and barometric pressure (base year 2014 summer period data were provided by TCEQ).
zonemonthhour	Meteorology	Local, hourly temperature and relative humidity for the county (2014 summer period data were provided by TCEQ).
Roadtype[i]	Activity	Lists the MOVES road types and associated ramp activity fractions. Road type ramp fractions were set to 0.
Hpmsvtypeyear[ii]	Activity	Used MOVES default national annual VMT by HPMS vehicle type.
roadtypedistribution[ii]		Used MOVES default road type VMT fractions.
monthvmtfraction[ii]		Used MOVES default month VMT fractions.
dayvmtfraction[ii]		Used MOVES default day VMT fractions.
hourvmtfraction[ii]		Used MOVES default hour VMT fractions.
avgspeeddistribution[ii]		Used MOVES default average speed distributions.
sourcetypeyear[ii]	Fleet	Used MOVES default national SUT populations.
sourcetypeagedistribution	Fleet	Local SUT age fractions estimated using Texas Department of Motor Vehicles (TxDMV) mid-year vehicle registrations and MOVES defaults, as needed. Used TxDMV latest available (2014) vehicle registrations for all years.
avft	Fleet	Local SUT fuel fractions estimated using TxDMV vehicle registration data, consistent with the data used in the

		sourcetypeagedistributions, and defaults where needed. Only gasoline and diesel were included, consistent with local VMT mix.
zone	Activity	Start, idle, and SHP zone allocation factors. County = zone, and all factors were set to 1.0 (required for county scale analyses).
zoneroadtype	Activity	SHO zone/roadtype allocation factors. County = zone, and all factors were set to 1.0 (required for county scale analyses).
fuelsupply	Fuel	Fuel supply, market shares were set to specify one RFG and one diesel fuel formulation.
fuelformulation	Fuel	Local gasoline and diesel formulations prepared by TTI. Used EPA RFG compliance survey sample data and TCEQ diesel survey data. The 2014 formulations were actual estimates and 2020 and later formulations were based on latest available summer (2017) actual estimates, with expected sulfur level values consistent with pertinent regulations. TTI set gasoline sulfur content to Tier 3 average annual standard and diesel sulfur consistent with federal ultra low sulfur diesel standard and recent local (TCEQ) diesel survey sample data.
imcoverage	I/M	Locality-specific I/M set-ups developed by TTI were used to represent the I/M program for each I/M county based on current I/M rules, latest modeling protocols, and the available MOVES I/M parameters (in terms of MOVES I/M "teststandards" and associated "imfactors") for the I/M vehicles.
countyyear	Stage II	Not applicable in analysis (affects refueling emissions), but included with control program adjustments set zero.

[1] In rates mode, ramp road type rates are not available.
[2] Use of a default set of activity and population inputs for all MOVES runs is basic to the inventory method (i.e., MOVES default activity is normalized in the calculated rates for applicable processes) and actual local activity estimates are used in the external inventory calculations.

Step 2—Create MOVES RunSpecs and Run MOVES

MOVES RunSpecs or MRS provides the instructions on how and what data to be used for estimating emission rates. Table 11 provides the RunSpecs information used for estimating emission rates. One RunSpec and one CDB are required per area per MOVES run. Each RunSpec is designed to produce a separate estimate, corresponding MOVES output database (i.e., one output database per run). Four MRS input files, four CDBs, and correspondingly four MOVES input and output databases were developed for the link-level analysis of this study.

After creating RunSpecs and using MOVES inputs identified in the previous step, MOVES runs were conducted for generating speed-sensitive emission rates. Emission rates in the MOVES output tables are provided by vehicletype, roadwaytype, pollutant, and emission processes combination, which requires post processing to be aggregated and formatted to a proper shape for the emissions impacts analysis of this project.

Table 11. Input Parameters for MOVES2014a Runs.

Input Item	Description
Run Specification	
Scale	Project Scale
Calculation Type	Emission Rate
Geographic Bounds	Dallas County, TX
Time Period	Analysis Years: 2015 Seasons: Summer (July) Time-of-day: AM Peak (6–9 a.m.), PM Peak (4–7 p.m.), Midday (9 a.m.–4 p.m.) and Overnight (8 p.m.–6 a.m.)
Road Type	Rural and Urban Restricted and Unrestricted Access
Vehicle Type	All
Pollutant Type	CO, NOx, VOC, CO_2, PM10, PM2.5
Emission Process	Running Exhaust, Crankcase Running Exhaust, (Brake and Tire Wear & Running loses where applicable)
Project Data Manager (Project Specific Input Data)	
Link Length	One mile
Average Speed	Ranging from 2.5 mph to 75 mph at 1 mph increment

Step 3—Develop VMT Mix

The VMT mix designates the vehicle types included in the analysis and specifies the fraction of on-road fleet VMT attributable to each vehicle type by day type (i.e., average weekday) and by MOVES road type. The VMT mixes were estimated based on TTI's 24-hour average VMT mix method, expanded to produce the four-period, time-of-day estimates (*75*). The procedure sets Texas vehicle registration category aggregations for MOVES categories to be used in the VMT mix estimates, as well as for developing other fleet parameter inputs needed in the process (e.g., vehicle age distributions). The VMT mix procedure produced a set of four-period, time-of-day average vehicle type VMT allocations by MOVES road type and by day type, estimated for each TxDOT district for use with the counties associated with each district. The data sources used were recent, multiyear TxDOT vehicle classification counts, year-end TxDMV registration data, and MOVES default data. For this analysis, 2015 VMT-Mix for the DFW area was used.

Step 4—Estimate Composite Emission Rates

Emission rates and VMT mix from previous steps were used to estimate composite emission rates for two broad vehicle types: light-duty vehicles and heavy-duty vehicles categories. The light-duty vehicles category represents passenger cars, passenger trucks (SUVs and pickup trucks), and motorcycles, while all other vehicle types (medium and heavy-duty trucks) are represented by the heavy-duty vehicles type. Composite emission rates corresponding to each category and roadway type were calculated using the following equations. In these equations, the subscript *i* is for vehicle types that make up the category:

$$\sum_i \textbf{\textit{Composite ER (LDV)}} = \textbf{\textit{Emission Rates (LDV)}} \times \textbf{\textit{VMTMix (LDV)}}$$

$$\sum_i \textbf{\textit{Composite ER (HDV)}} = \textbf{\textit{Emission Rates (HDV)}} \times \textbf{\textit{VMTMix (HDV)}}$$

Mesoscopic Modeling

The outputs of DynusT provide the vehicle activity inputs to emission estimation. Total daily emissions were calculated using the accumulative link volumes and link average speeds output files. The data associated with each link (i.e., speed and volume) were used to estimate the total VMT, average speed, total emissions, and other metrics for the study corridor and the selected influence zones. The outputs of DynusT are in the form of vehicle volumes (cars and trucks) on each link and their corresponding average link speeds at 1-minute intervals. For each scenario (i.e., base and metered), three output tables were generated by the DynusT: accumulative car volumes, accumulative truck volumes, and link average speeds. Researchers constructed a data model of the required tables in Power BI as shown in Figure 24. The following steps were implemented using the DAX language to estimate the link-level emissions:

1. Extract 1-minute car and truck volume from accumulative volumes for each scenario (base and metered).
2. Calculate 1-minute car and truck VMT for each link.
3. Aggregate car and truck VMT to a 15-minute interval.
4. Calculate VMT-weighted average speed for each 15-minute interval.
5. For each 15-minute period, apply the corresponding speed-sensitive composite emission rate to each link's car and truck VMT. Average vehicle speed, road type, and vehicle type are used to identify the appropriate emission rate.
6. Calculate the total emissions for the influence zone by summing the emissions generated on each link for the desired analysis timeframe.

The results are 15-minute link-level emissions for each scenario (base and metered). Because the modeled ramp metering scenarios are only for morning and afternoon peak, the timeframe for the emissions analysis was set to 5 a.m. to 8:59 p.m.
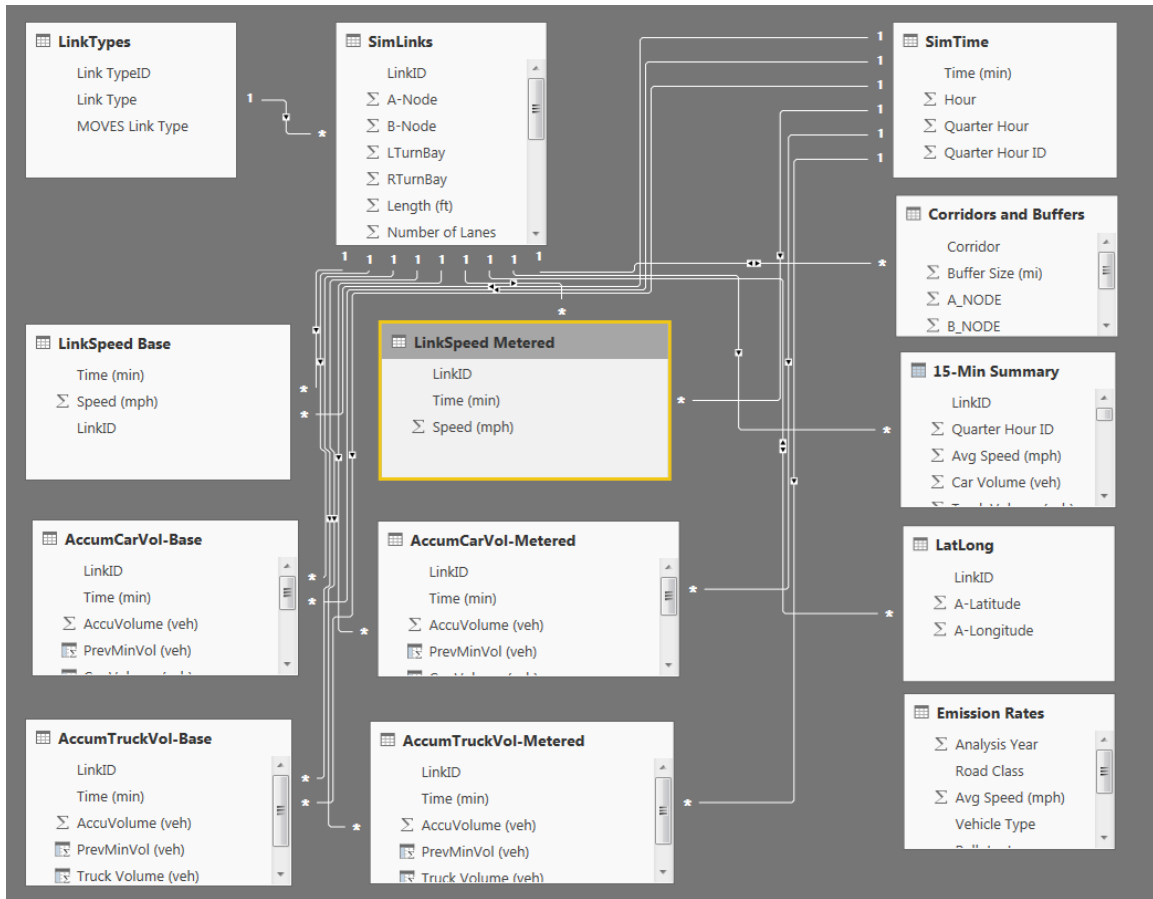
Figure 24. Data Model for Estimating Emissions from DynusT Outputs.

As mentioned previously, the analysis is based on an influence zone approach to determine the regional emission impacts of the ramp metering. There are various methods to determine the influence zone of a transportation strategy, which vary in complexity and parameters they use. Researchers determined that a simplistic distance-based definition of influence zone is adequate for this study (i.e., a high-level characterization of the potential changes in emissions as the results of ramp metering along a specific corridor). Figure 25 shows examples of the influence zones used in the emissions analysis. A zero-buffer distance represents the freeway corridor links that were subject to metering (i.e., freeway corridor only).
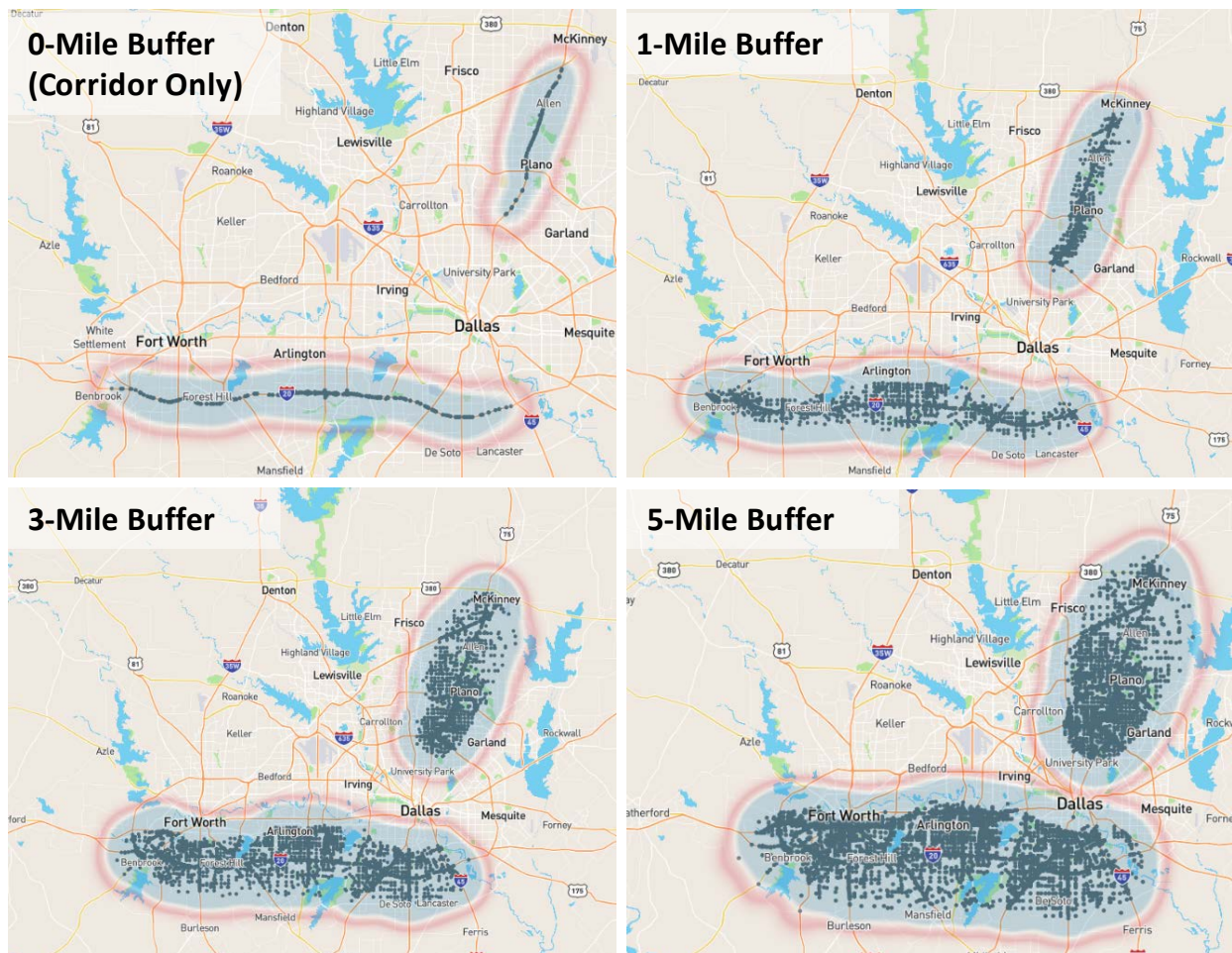
Figure 25. Examples of Influence Zones Used in Emissions Analysis.

Microscopic Modeling

The link-level outputs of VISSIM were used as the vehicle activity inputs to emission estimation. Total daily emissions changes were calculated using the 15-minute link volumes and link average speeds. The data associated with each link (i.e., speed and volume) were used to estimate the total VMT, average speed, total emissions, and other metrics for the study corridor. The link-level outputs of VISSIM used in this analysis included vehicle volumes (cars and trucks) on each link and their corresponding average link speeds at 15-minute intervals. For each scenario (i.e., base, strict metering, and flush metering), one output table was generated by VISSIM. The overall emissions analysis methodology is the same as the one used for the mesoscopic model; the estimation process is slightly different from the mesoscopic analysis because of the differences of how outputs are reported in the VISSIM model. The analysis is based on the link-level traffic information that was averaged for five VISSIM runs as described in the traffic simulation section.

Researchers constructed a data model of the required tables in Power BI. The following steps were implemented using the DAX language to estimate the link-level emissions.

1. For each link, extract 15-minute car and truck volume and average speed for each scenario (base, strict metering, and flush metering).
2. Calculate 15-minute car and truck VMT for each link.
3. For each 15-minute period, apply the corresponding speed-sensitive composite emission rate to each link's car and truck VMT. Average vehicle speed, road type, and vehicle type are used to identify the appropriate emission rate.
4. Calculate the total emissions for the study area by summing the emissions generated on each link for the desired analysis timeframe.

The results are 15-minute link-level emissions for each scenario. Because the modeled ramp metering scenarios are only for morning and afternoon peak, the timeframe for the emissions analysis was set to 5 a.m. to 8:59 p.m. The network used in the mesoscopic analysis include the corridors' freeway links (including ramps), frontage roads, and connecting arterials. The microscopic network includes a shorter section of the studied corridors than the mesoscopic model.

FIELD STUDIES

To evaluate the impact of ramp metering on emissions as vehicles traverse a metered ramp, researchers collected data at five on-ramps located along a southbound section of I-45 in Houston as shown in Figure 26. TxDOT has recently upgraded ramp controllers at these ramps and re-activated metering after months of no metering operation.

Data collection involved the use Portable Activity Measurement System (PAMS) data loggers. The PAMS units recorded GPS and engine parameters (via CAN bus) at 1 Hz frequency. Researchers used two vehicles (a 2009 Ford Explorer and a 2011 Ford 250 XLT truck) with PAMS mounted onto OBD-II ports for this study. Researchers collected before (no-meter on) data for three days in 2017, during December 12 through 14. Using the same vehicles and same drivers, researchers collected data with operating meters during April 10–12, 2018.

For both sets of runs, researchers followed the same starting point and path, which included entering freeway at each ramp, exiting at the freeway at a specific ramp, and the U-turn point after traversing the last metered-on ramp. Figure 26 shows the starting point, each entrance ramp traversed, and the U-turn location. Drivers started the runs according to the schedule in Table 12. This schedule provided 40 minutes to return to the starting point, where the driver waited until the start time for the next run.

Table 12. Vehicle Departure Schedule.

Run	Vehicle 1	Vehicle 2
1	5:30 AM	5:50 AM
2	6:10 AM	6:30 AM
3	6:50 AM	7:10 AM
4	7:30 AM	7:50 AM
5	8:10 AM	8:30 AM
6	8:50 AM	9:10 AM
7	9:30 AM	9:50 AM
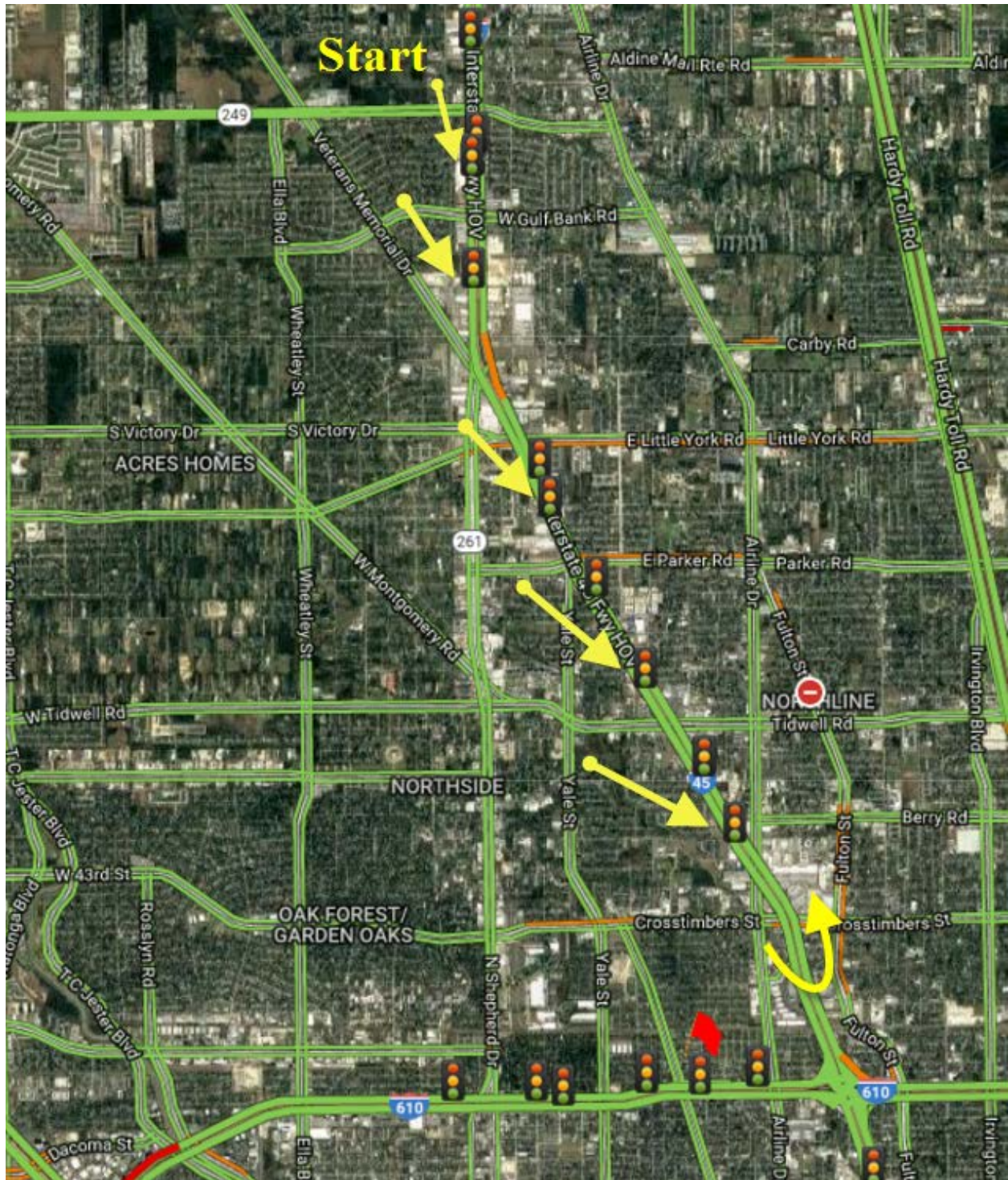
Figure 26. Houston Field Study Location.

After collecting all data, researchers used second-by-second engine performance and activity parameters (i.e., engine speed, engine load, fuel consumption, exhaust temperature) to establish on-ramp OpMode distributions for baseline (i.e., no ramp metering) and ramp metering cases.

Collected data also include spatial location of the vehicle at each second. Researchers followed the steps listed below to process the data:

1. All the waypoints derived from the study were plotted in ArcGIS and overlaid on road network of the region.
2. ArcGIS's spatial join tool was used to associate each waypoint with the closest road segment.
3. All the waypoints associated with the ramps were extracted by the functional classification of the road networks.
4. On-ramp segments (i.e., from frontage road to freeway) were visually identified and marked. The data within these segments were extracted using their spatial and temporal sequence.
5. OpMode for each waypoint of the filtered data was calculated using the MOVES parameters and equations. MOVES vehicle type 31 (passenger truck) was used for this purpose.
6. MOVES emission rates were used to calculate the instantaneous emissions for each waypoint.
7. The second-by-second emissions were aggregated for all the filtered data to get the total emissions before and after ramp metering deployment.

STUDY RESULTS AND RECOMMENDATIONS

MESOSCOPIC ANALYSIS

Traffic Performance

Appendix C contains plots comparing traffic performance for US 75 micro- and meso-corridor limits as identified in Figure 15. Figure C1 provides a visual comparison of meso and micro limits for 0-mile buffer (freeway links only). Figure C2 together with Figure C1 illustrate the influence zones of 0-, 1-, and 3-mile zones for the larger meso-corridor. Figure C3 provides comparisons of one-shot and UE results for 0-mile, 1-mile, and 3-mile buffers. The following observations are drawn from this figure:

- For the one-shot case, as illustrated in Figure 27:
  - Average freeway speeds (0-mile buffer) for the metering scenario are consistently better than the no-metering scenario during both metering periods.
  - As the buffer size increase, average corridor speed for metering scenario converges toward the no-metering scenario but remains slightly higher.
  - There are no significant shifts in VMT for the freeway links. However, with larger buffer sizes that include ramps and more surface street links, VMT shows a decreasing trend. This implies that ramp metering is negatively impacting surface streets and the gain in speed on the freeway is countered by reduction in speeds on the surface streets.
- The ramp metering with UE scenario, illustrated in Figure 28 provides the following information:
  - Ramp metering continues to result in improved freeway speeds even after drivers had a chance to adjust to changes.
  - As buffer size is increased to include more and more adjacent roadways, average speeds for metering scenario converge to the no-metering case.

As illustrated in Figure C4, the results related to speed improvements and changes in VMT are similar between the micro-corridor and the meso-corridor.

Appendix D compares metering and no-metering scenario results for the I-20 corridor. Figure D1 illustrates the limits of I-20 micro-corridor and macro-corridor limits for 0-mile, 1-mile, and 3-mile buffers. Figure D2 compares one-shot and UE metering scenarios against the base case for the EB direction.
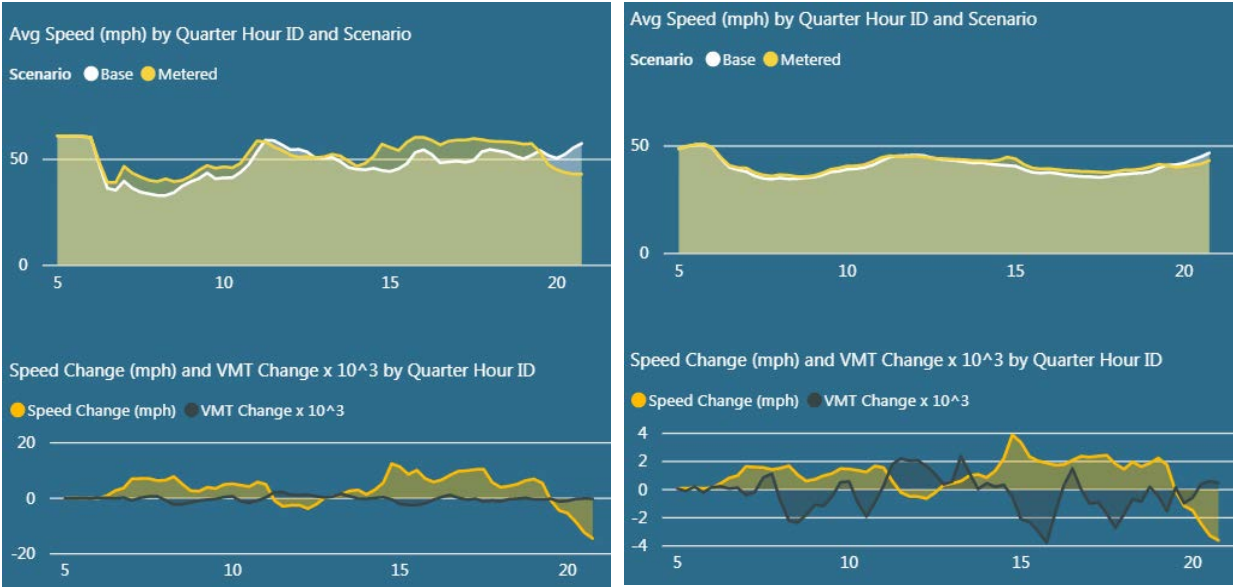
Figure 27. Comparison between Results for 0-Mile and 1-Mile Buffers for One-Shot Scenario.
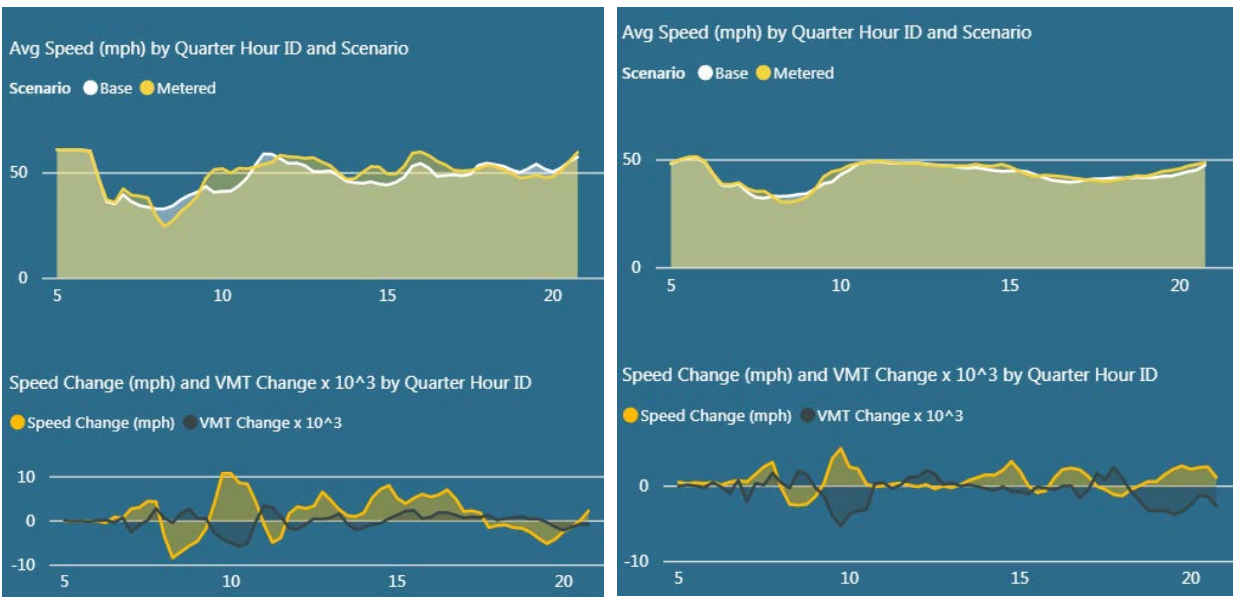
Figure 28. Comparison between Results for 0-Mile and 1-Mile Buffers for UE Scenario.

For the EB directions, Figure D2 provides the following information:

- There is a slight immediate improvement (the one-shot case) in freeway speeds during AM- and PM-peak periods, followed by a decrease in speed at the end of PM-peak metering. This increase coincides with an increase in freeway VMT. Except the scale of peaks and valleys between micro- and meso-corridors, the trends for the two corridor limits are almost same.

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- For the UE case, however, significant changes in freeway speeds occur in the AM-peak period. In this case, freeway speeds increase initially, then decrease and then increase again, with an overall positive impact on freeway speeds during AM-peak. The positive impact is more pronounced in the micro-corridor.

For the WB direction (as illustrated in Figure D3):

- Freeway speed increases due to ramp metering are seen mostly during the PM-peak period for the one-shot case.
- The UE case shows that the above improvement in freeway travel speeds attracted move vehicle to the freeway, diminishing positive impacts.

Emissions

Figure 29, Figure 30, and Figure 31 show the total emissions and 15-minute travel times (freeway corridor only) resulting from the mesoscopic modeling corresponding to user-equilibrium conditions. Because both directions of I-20 are included in the case study analysis, the results are presented for both morning and afternoon periods. The traffic congestion is mainly present during the morning period for the US 75 SB corridor, only the morning period results are shown. In interpreting the results, the mesoscopic traffic modeling represents a simplified scenario for the entire corridors. The analysis results are therefore a high-level indication rather than exact expected changes for a specific ramp metering implementation.

The emissions results shown in Figure 29 and Figure 30 suggest that ramp metering along neither direction of the I-20 corridor may result in a total NOx reduction. This trend is true during the combined AM and PM period and the AM and PM periods individually, for all the influence zone sizes less than 5 miles. The 5-mile influence zone shows a very small decrease in NOx, which is practically equivalent to no change. For the other pollutants on the other hand, the ramp metering on both directions in the AM period seems to result in a reduction.

The results shown in Figure 31 suggest that ramp metering along the US 75 SB corridor may result in a NOx reduction for all influence zone sizes. The reduction ranges from slightly over 2 percent for the corridor's freeway links only (i.e., 0-mile influence zone) to approximately 1 percent for the 5-mile influence zone. All the other pollutant emissions also reduced because of ramp metering. Particulate matter had the highest and CO_2 had the lowest percentage of potential reduction. In interpreting the above results, the percentage differences are relative to the base for that influence zone. As the size of the analyzed influence zone grows so does the total emissions for it. For example, a 2 percent NOx reduction for the corridor's freeway links is equivalent to approximately 11 kg/day while a 1 percent reduction for the 5-mile influence zone is equivalent to 61 kg/day.
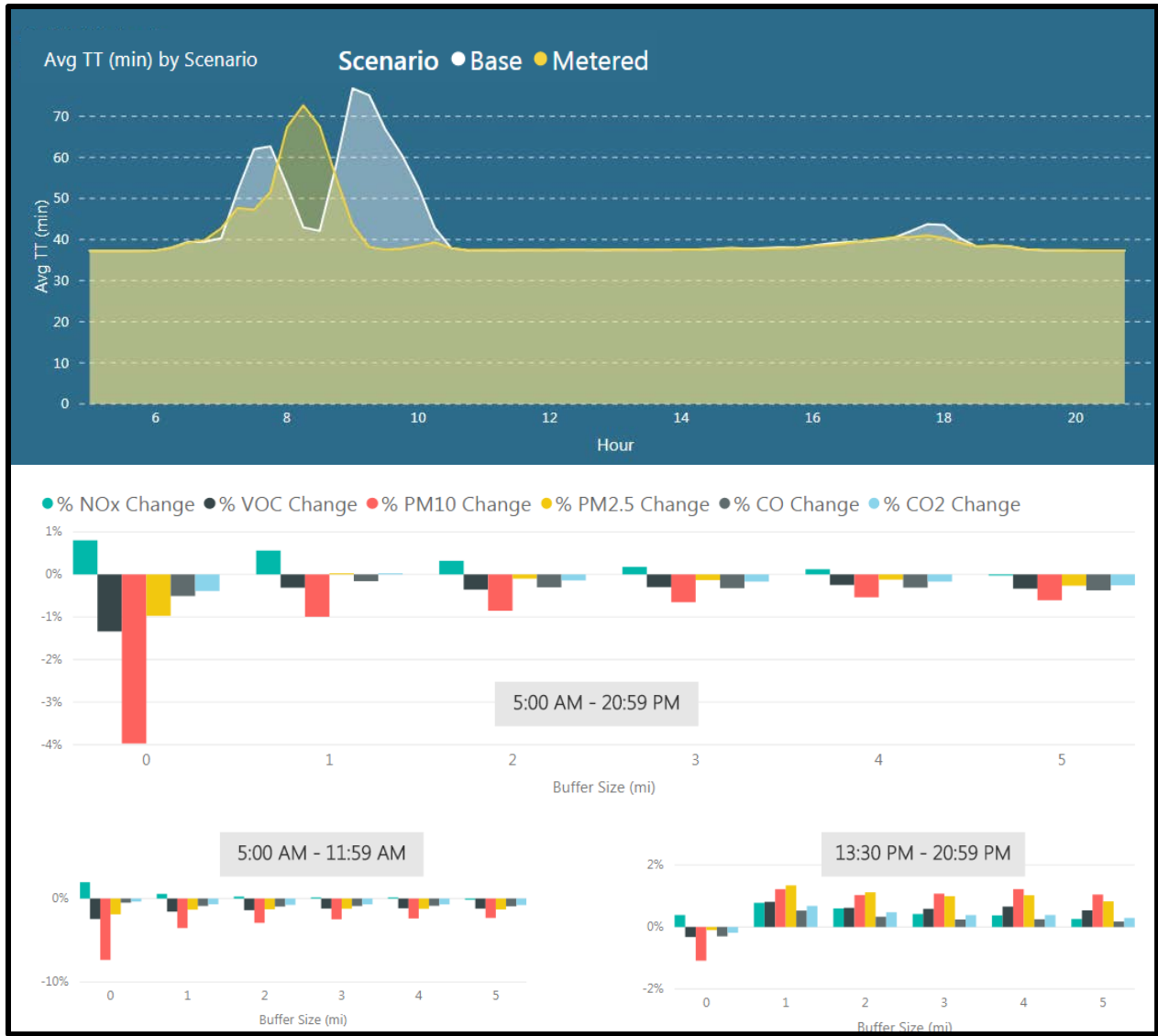
Figure 29. Emissions and Freeway Corridor Travel Time for I-20 EB.
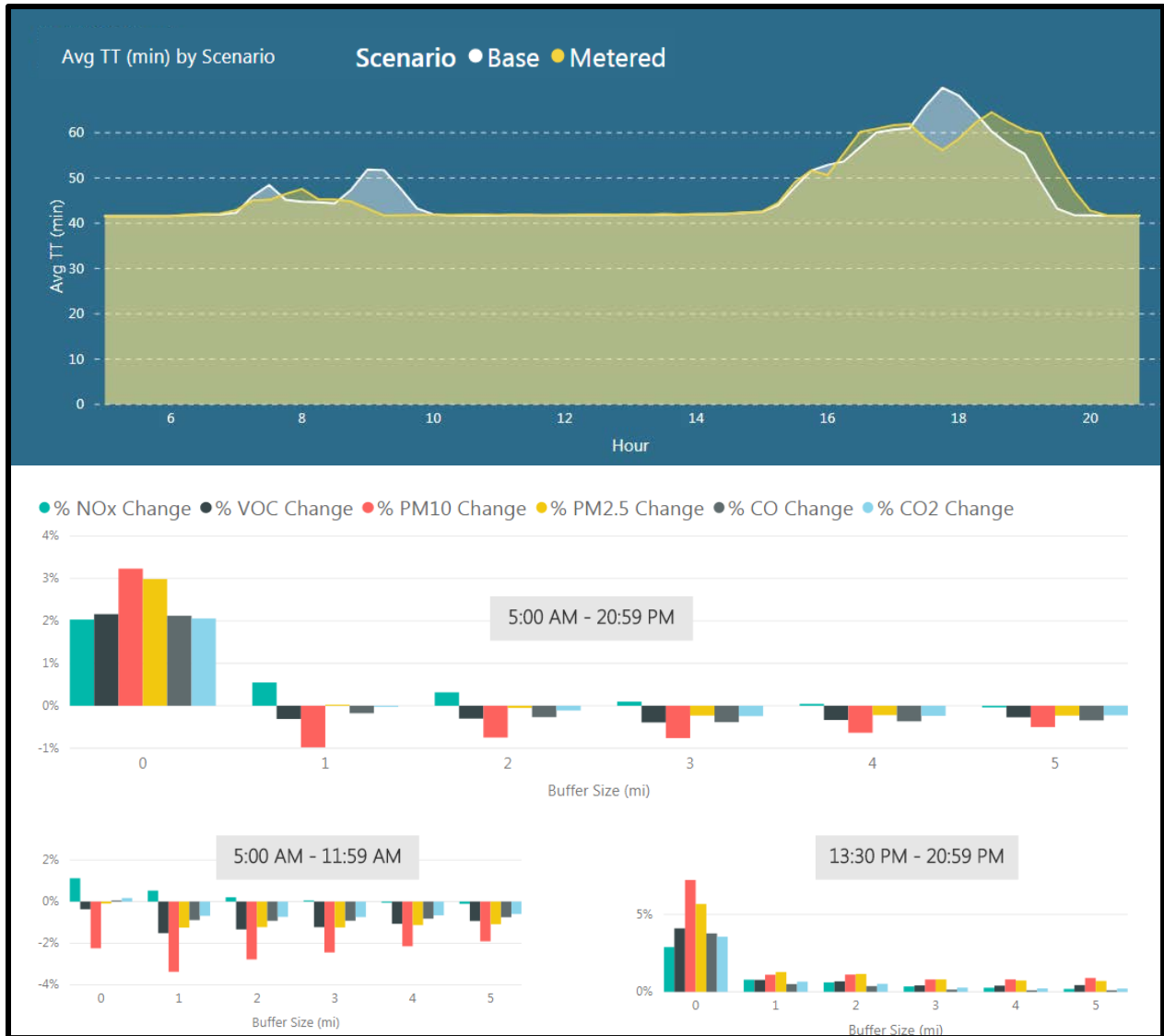
Figure 30. Emissions and Freeway Corridor Travel Time for I-20 WB.
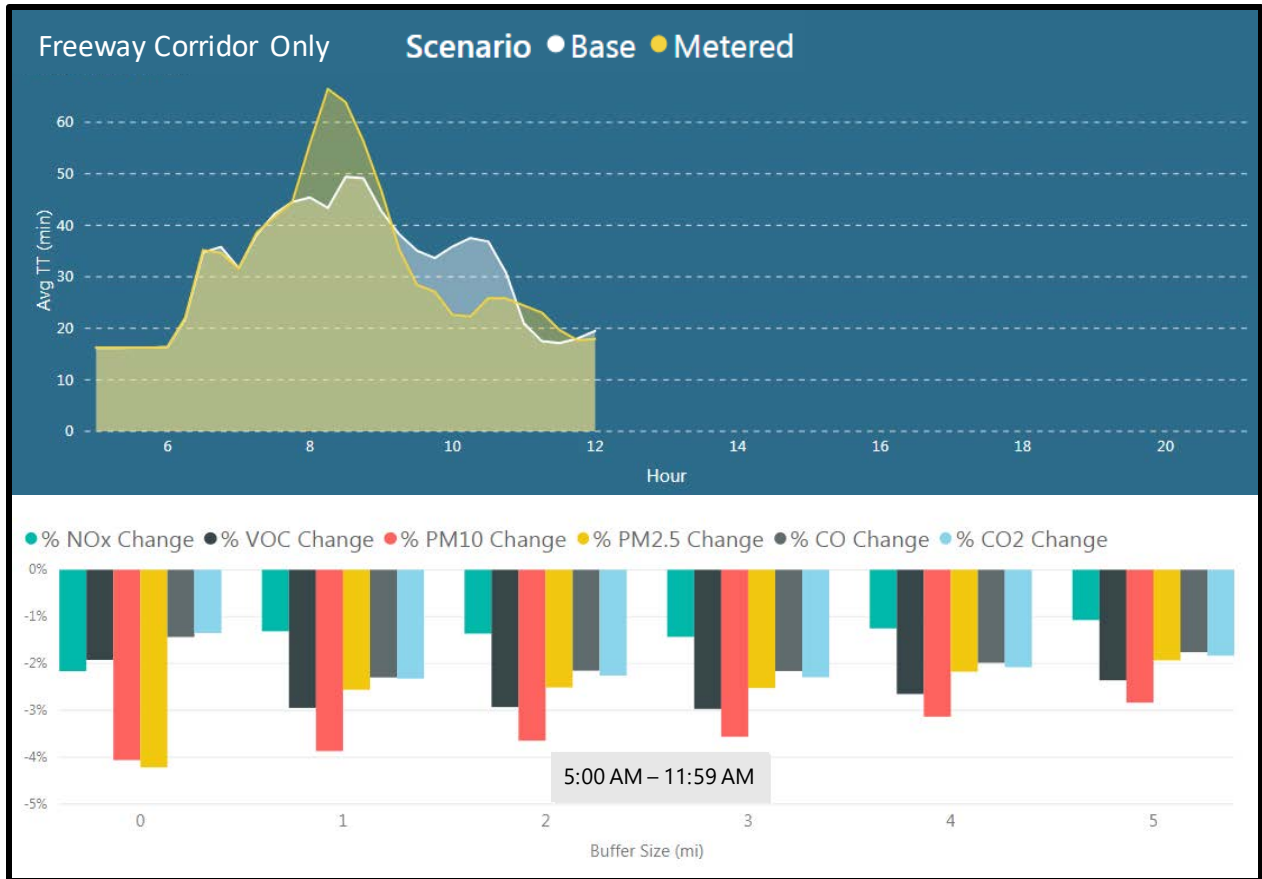
Figure 31. Emissions and Corridor Travel Time for US 75 Southbound.

Changes in vehicular emissions from a transportation strategy are the result of combination of factors such as changes in VMT, speed, and vehicle mix. To better understand the potential of the ramp metering in reducing NOx emissions on the US 75 corridor, researchers examined changes in VMT and NOx broken down by road type (freeway versus non-freeway) and vehicle type (car versus truck). Graphs in Figure 32 show the results of this examination. The following observations are made based on these graphs:

- Ramp metering can potentially reduce NOx from the corridor's freeway links (i.e., buffer size 0).
- As the size of the influence zone increases (i.e., adjacent freeways and arterials are included in the analysis), the NOx emissions reductions from freeway links shrink and even increase for the 4- and 5-mile influence zones.
- When arterial links are included (i.e., buffer zone 1-mile and larger), the majority of the potential NOx reduction is from arterial links.
- Overall average speed for the analysis period increases for both arterial and freeway links. These changes suggest an improvement in the overall movement of vehicles on the included links.
- The car and truck VMT for the freeway links of the metered corridor (0-mile influence zone) show a slight reduction for the metered condition compared to the base condition. When the adjacent freeway links are included (i.e., 1-mile or larger influence zone), the

freeway VMTs show an increase. The links included in these larger influence zones are associated with the longer segment of US 75 and other freeways that connect to US 75.

- Compared to the base condition, the arterial links' VMTs (car and truck) are reduced for the metered scenario.
- The size of the reduction in arterial VMTs grows as the size of the influence zone increases. An opposite trend is observed for the freeway links (i.e., the growth of freeway VMTs increase as the size of the influence zone grows). Furthermore, the magnitude of the arterial VMT increases is between 2.6 and 5 times of the freeway reductions. This trend suggests that the ramp metering on US 75 has potentially resulted in:
  - o An overall improvement in traffic flow on the freeway links within the influence zone of the metered corridor.
  - o As a result, some arterial trips for the base case are now using freeways in the area, which results in overall reduction of VMT in the influence zone.
  - o The reduction of VMT in turn is the main driver of the expected NOx reduction after implementation of ramp metering.
- Heavy-duty diesel trucks have a much higher per vehicle emission rate than light duty gasoline vehicles, so a small change in their VMT translates into a large change in the total NOx impacts of the ramp metering, as shown in Figure 32.
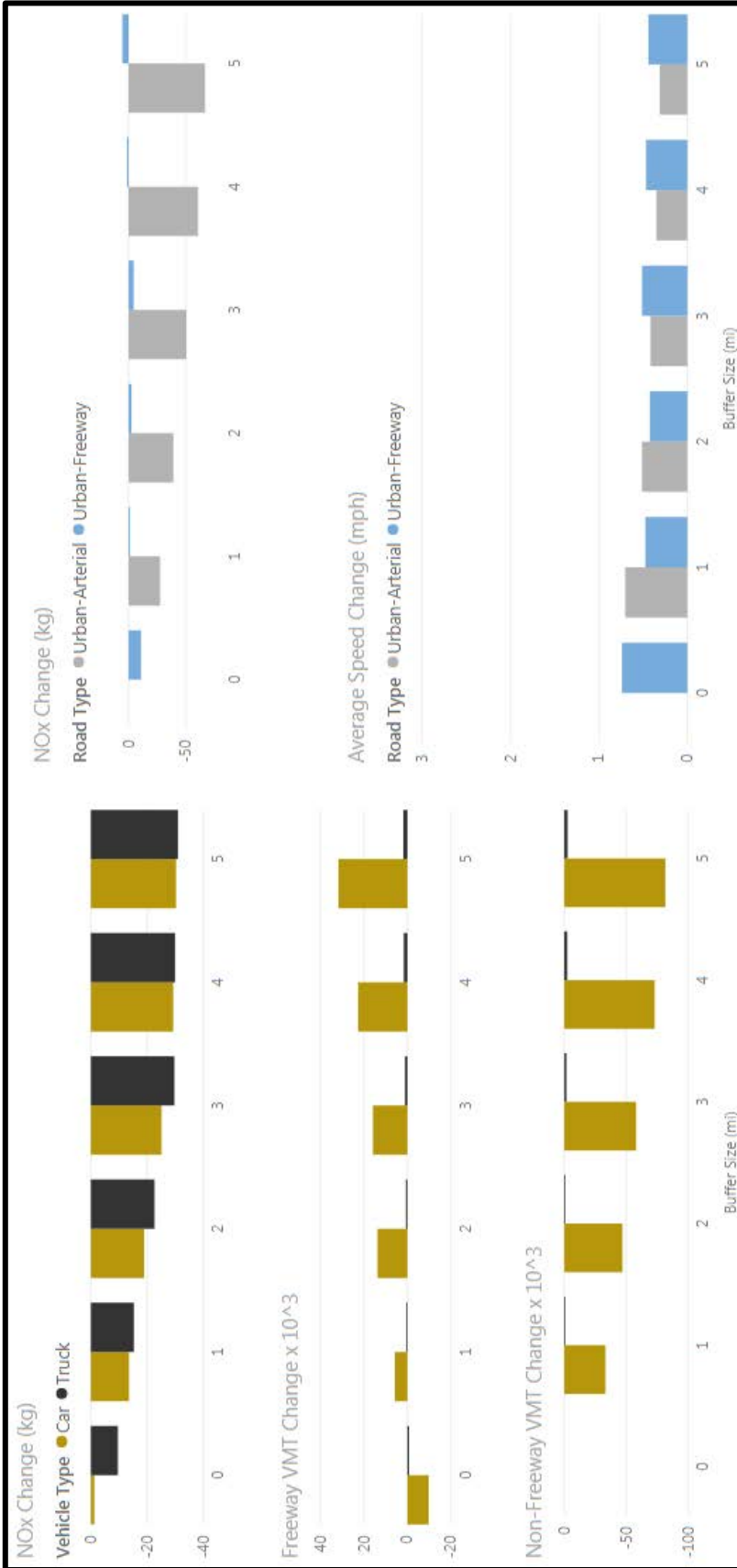
Figure 32. Changes in Emissions and Freeway Activity for US 75 Southbound – UE.

RESULTS OF MICROSCOPIC ANALYSIS

Results presented in this section are averages of five replications for each scenario simulated in VISSIM.

Traffic Performance

Figure 33 shows a graph of freeway travel time for the US 75 corridor from 6:00 a.m. to 6:00 p.m. As shown by this graph, strict metering provides the best freeway performance (lowest travel time) during AM-peak metering operation. However, freeway travel time increased at the end of strict metering and remained elevated for almost 45 minutes. The red circle in Figure 33 highlights this increase, the cause of which is the release of excess ramp demand blocked from entering during metering, which ends at 9:15 a.m. Figure 34 and Figure 35 show total travel time and total delay from 6:00 a.m. to 6:00 p.m. These graphs show that strict metering results in significantly higher values for both these performance measures during AM-peak metering. These negative impacts linger for almost an hour after metering ends and show that the delay cause to surface street vehicles outweigh improvements to freeway flow. Further inspection of simulation results for this case shows that the cause of excessive delay is mainly from one ramp where excess demand caused traffic blockage at the upstream signal and beyond. This situation is not permissible.
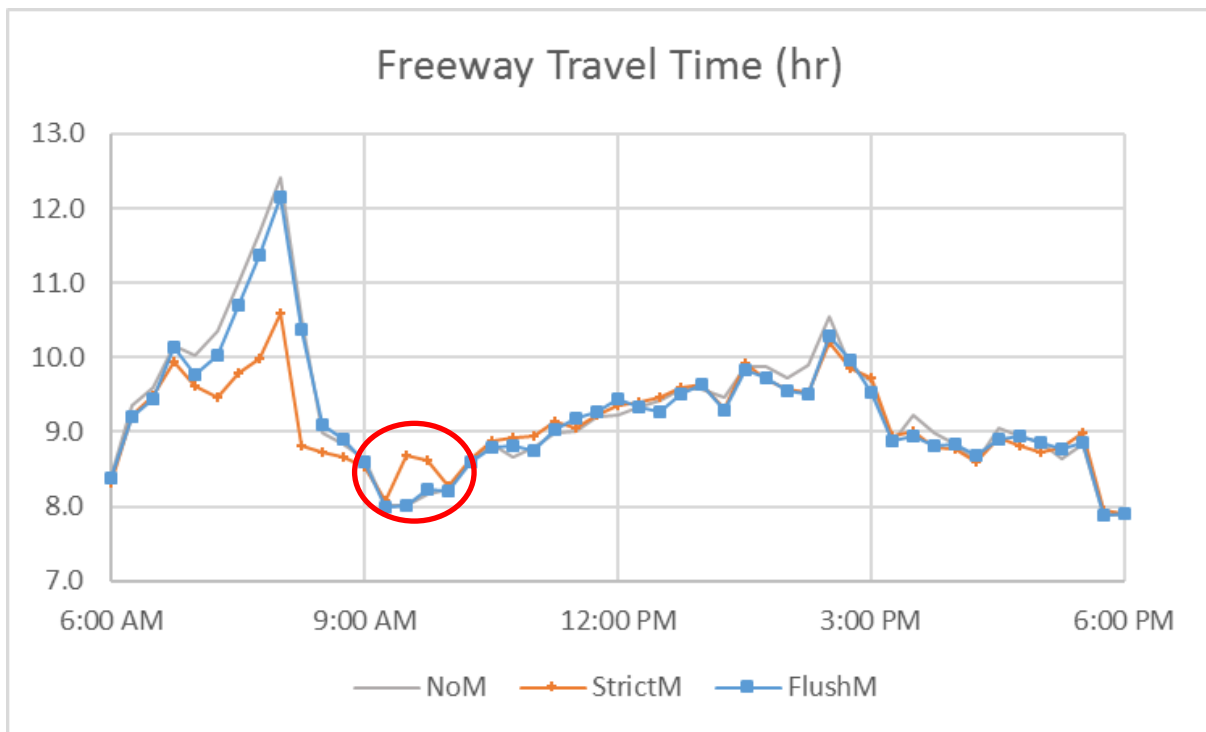
Figure 33. Freeway Travel Time for US 75 Corridor.
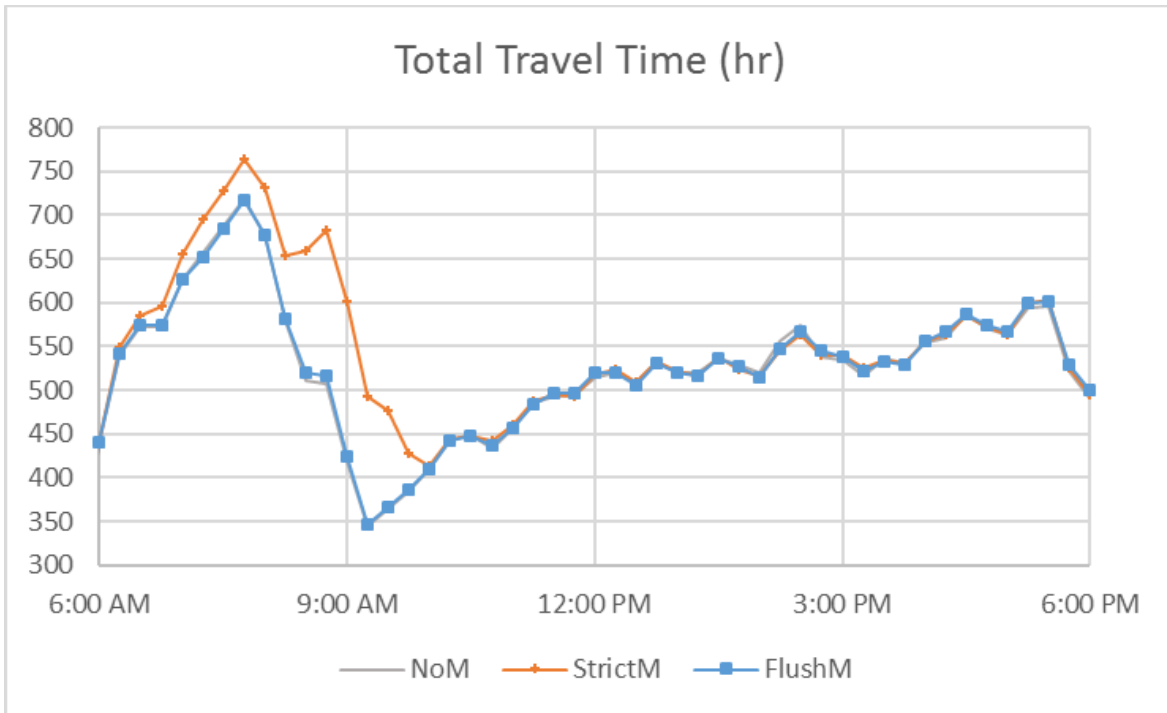
Figure 34. Total Travel Time for US 75 Corridor.

Figure 35. Total Delay for US 75 Corridor.

The above graphs also show that ramp metering with queue flush provide slight improvement over no metering during morning peak period, without any significant degradation in total travel time and delay. These graphs also show that during lighter PM-peak traffic conditions, performance of both metering strategies is about the same with slightly better freeway travel times than no metering and without much degradation to surface-street traffic. However, these differences are small.

Figure 36 shows heat diagram of freeway speeds downstream of ramp merge for all ramps and all three strategies. Here, the darker the color, the slower the speed. The top part of this figure shows AM-peak period plus an hour after and the bottom portion shows the PM-peak period.

Time	NoM											StrictM											FlushM									
	1	2	3	4	5	6	7	8	9	10		1	2	3	4	5	6	7	8	9	10		1	2	3	4	5	6	7	8	9	10
6:00 AM	56	58	55	54	48	46	47	47	47	48		56	57	55	53	49	47	46	48	47	48		56	57	55	53	48	47	46	47	47	48
6:15 AM	54	58	56	54	47	42	40	39	41	42		55	57	55	53	48	43	44	40	41	42		55	57	55	54	47	42	41	43	41	43
6:30 AM	54	57	55	50	46	41	40	40	40	41		54	56	55	52	47	42	40	41	41	42		55	56	55	49	46	42	39	42	40	41
6:45 AM	55	58	56	52	46	39	38	37	39	41		56	57	56	52	47	41	40	38	40	39		56	57	56	53	46	40	39	37	39	40
7:00 AM	54	58	55	51	46	39	39	38	39	39		55	57	54	51	48	44	42	40	40	38		56	57	54	51	46	43	40	38	40	38
7:15 AM	54	57	54	52	45	39	36	39	41	40		55	56	54	51	46	42	38	42	41	40		55	57	54	51	45	39	35	40	40	41
7:30 AM	54	57	54	52	44	37	33	35	40	39		55	57	53	51	46	41	37	39	41	40		55	57	53	51	44	38	34	35	40	40
7:45 AM	55	57	53	50	43	35	32	33	39	39		56	56	53	50	45	40	38	35	40	39		56	56	53	50	41	36	34	33	40	38
8:00 AM	54	57	54	52	46	36	35	32	39	39		55	57	54	51	46	41	39	36	39	39		54	57	54	53	43	38	35	33	40	40
8:15 AM	53	58	55	54	48	44	43	36	39	39		56	58	55	54	49	47	47	46	41	41		54	57	54	53	48	43	42	40	39	38
8:30 AM	54	58	55	53	48	46	45	42	41	40		57	57	55	54	49	47	46	46	43	43		54	57	54	52	47	45	44	43	42	42
8:45 AM	54	57	55	53	47	45	45	44	43	42		56	57	55	53	48	46	46	46	43	44		54	57	54	53	47	45	44	43	42	42
9:00 AM	56	57	54	52	48	46	45	45	43	43		56	57	55	53	49	48	46	46	44	44		56	57	54	52	48	46	45	45	43	42
9:15 AM	56	56	53	52	48	48	48	48	47	47		54	55	53	51	48	48	48	48	47	47		56	56	53	52	48	48	48	49	48	48
9:30 AM	55	56	53	51	47	48	48	49	47	47		53	54	52	49	43	42	42	41	42	42		55	56	53	51	47	48	48	48	47	47
9:45 AM	56	56	53	52	48	48	48	48	46	46		55	56	53	52	46	47	47	45	42	42		55	56	53	52	48	48	48	47	46	45
2:30 PM	54	56	52	48	41	39	39	33	39	38		54	55	53	45	41	39	39	38	39	39		55	55	53	48	43	39	38	37	39	38
2:45 PM	53	56	53	48	44	39	41	40	39	39		54	55	53	48	43	40	40	39	39	39		53	55	53	49	45	42	40	37	39	40
3:00 PM	54	57	54	51	46	43	42	41	41	40		54	57	54	51	46	43	43	39	42	41		55	57	54	51	46	43	43	42	40	40
3:15 PM	54	57	54	49	46	45	45	46	44	44		55	56	54	52	48	47	46	44	43	43		55	56	54	51	47	45	45	45	44	44
3:30 PM	55	57	54	52	47	44	45	44	43	42		56	56	54	52	48	45	44	44	43	42		55	56	55	52	48	46	45	44	43	42
3:45 PM	55	58	54	52	47	45	44	43	43	43		56	57	55	52	48	45	45	45	43	44		56	57	55	53	48	46	44	44	44	44
4:00 PM	55	58	55	53	49	46	46	44	42	42		56	57	55	53	49	47	46	45	43	43		56	57	55	53	49	46	46	45	43	43
4:15 PM	55	57	55	53	49	47	48	46	44	44		56	56	55	53	49	48	47	46	44	45		56	56	55	53	49	47	46	46	43	43
4:30 PM	56	57	54	53	48	45	45	44	43	42		56	57	54	52	48	45	45	44	43	44		56	56	54	53	48	46	45	45	43	43
4:45 PM	54	57	54	52	48	44	45	44	43	42		56	57	54	52	49	46	45	45	43	42		55	57	54	51	48	45	44	45	42	42
5:00 PM	56	58	55	54	49	46	47	45	42	43		56	57	55	53	49	47	46	46	43	43		56	57	55	53	49	46	45	46	43	43
5:15 PM	56	58	54	52	48	47	47	46	45	45		56	57	54	52	47	46	46	46	44	45		56	57	54	52	48	46	46	47	44	44
5:30 PM	58	60	56	57	53	47	48	47	42	42		57	58	56	55	51	47	47	46	42	43		57	58	56	57	52	48	47	47	42	43
5:45 PM	59	60	57	59	55	53	56	55	49	55		58	58	57	58	55	53	55	55	49	54		58	58	57	58	55	53	55	56	49	54
6:00 PM	58	61	58	57	55	52	56	55	51	55		57	59	58	57	55	52	55	55	51	55		57	59	58	57	55	53	55	55	51	54
6:15 PM	58	60	57	55	55	51	56	55	49	54		57	58	57	56	55	51	55	55	48	54		57	58	57	56	55	52	55	55	49	53
6:30 PM	58	61	58	58	55	52	56	55	49	54		58	59	58	57	55	52	55	55	49	54		58	59	58	57	55	52	55	55	49	53
6:45 PM	58	61	58	57	55	52	56	55	49	55		58	59	58	57	55	52	55	55	50	54		57	59	58	57	54	52	55	55	49	54

Figure 36. US 75 Heat Diagrams for Speeds Downstream of Merge for All Ramps.

This figure provides the following observations about the simulated traffic conditions:

- For the first four ramps, neither metering strategy affected freeway speeds downstream of the merge area.
- For the remaining six ramps, metering with queue flush operation is slightly better than no metering. In addition, strict metering is the best for freeway traffic, but freeway speeds drop immediately after metering ends.
- For the PM-peak metering versus no metering, results are not very different and any improvement resulting from metering could be due to randomness.

Table 13 shows flush statistics for the 10 ramps for AM-peak and PM-peak metering periods. These data show the following high flush rates:

- Ramp Meter 1 flushed 14 percent of time from 8 a.m. to 9 a.m. This is an acceptable metering availability of 86 percent (100 minus 14) as per Figure 4, though results presented above suggest metering is not needed at this ramp for the simulated freeway conditions
- Ramp Meter 4 flushed 10 percent during the hour starting at 7 a.m., and acceptable metering availability of 90 percent as per Figure 4.
- Ramp Meter 5 flushed during the first three hours during AM-peak period. Flushing percent during both hours between 7 a.m. to 9 a.m. are high, suggesting that the meter quality is fair during this time. This meter can significantly benefit from a dual-lane meter. In the strict metering case, the release of traffic backed up at this ramp caused degraded freeway flow immediately after metering period ended.
- At all other times and ramps, there was either no flushing or it was not significant.

Table 13. Flush Statistics for US 75.

Ramps Flushes in Percent of Hour										
Hour	1	2	3	4	5	6	8	7	9	10
6	1.3%	0.0%	0.0%	1.1%	9.1%	1.9%	0.0%	0.0%	0.0%	0.0%
7	4.2%	0.0%	3.1%	10.0%	22.3%	2.0%	0.0%	0.0%	0.0%	0.0%
8	14.0%	0.0%	0.4%	2.8%	18.8%	0.2%	0.0%	0.0%	0.0%	0.0%
9	0.1%	0.0%	0.3%	0.0%	0.8%	0.1%	0.0%	0.0%	0.0%	0.0%
14	0.4%	0.0%	0.3%	4.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
15	3.2%	0.0%	0.6%	1.2%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%
16	1.4%	0.0%	1.1%	1.6%	1.2%	0.5%	0.0%	0.0%	0.0%	0.0%
17	1.1%	0.0%	0.4%	0.4%	0.2%	0.3%	0.1%	0.0%	0.0%	0.0%
18	0.2%	0.0%	0.1%	1.4%	0.2%	3.0%	0.0%	0.0%	0.0%	0.0%
19	0.0%	0.0%	0.0%	0.6%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%

Table 14 shows maximum ramp queue at the merge area. These values are in feet, so a value of 100 would be equivalent to four vehicles assuming effective length of 25 ft/vehicle. Darker color means more vehicles. This figure provides the following information:

- In the no-metering case, queue in the merge area means that vehicles are unable to find a gap to merge. This could be because of platooned arrival of multiple vehicles or other reasons, such as non-optimal merge area geometry.
- The table shows that strict metering reduced maximum queues, as signified by reduction in cells with darker colors. However, it fails to prevent queues, possibly because platooning is only one case of queueing.
- Maximum queues for metering with queue flush operation is also less than no-metering scenario, but higher than strict metering, meaning that it also helps improve merge operation.

Table 14. Max Queue (ft) at Merge Area.

Time	No Metering										Strict Metering										Metering with Flush									
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
6:00 AM	0	0	78	116	19	109	0	0	66	0	27	0	48	119	81	69	0	0	9	0	0	0	46	94	81	25	0	0	4	0
6:15 AM	41	0	77	104	0	182	0	0	70	0	28	3	75	58	85	132	0	0	21	0	69	13	0	66	85	167	0	0	15	0
6:30 AM	45	9	80	114	27	218	0	0	84	0	96	0	45	128	85	188	0	0	26	4	44	35	44	117	85	216	0	0	31	0
6:45 AM	23	0	22	132	13	237	0	0	40	0	6	0	9	125	85	243	0	0	5	0	0	7	9	97	74	274	0	0	3	0
7:00 AM	56	0	91	136	38	227	0	5	65	0	95	0	105	139	84	101	0	0	11	0	53	0	125	139	81	174	0	0	26	0
7:15 AM	57	6	156	114	49	172	0	0	122	0	101	21	203	141	81	101	0	0	26	0	12	0	195	138	70	105	0	0	20	0
7:30 AM	15	0	102	127	26	281	0	11	53	0	25	6	165	137	85	150	0	0	30	0	14	0	181	138	78	275	0	5	7	0
7:45 AM	53	15	82	139	44	265	0	0	73	0	0	24	125	146	85	290	0	7	17	0	54	26	173	135	81	266	0	0	26	4
8:00 AM	83	0	73	119	13	205	0	0	127	3	60	0	53	139	85	170	0	0	50	0	146	0	53	130	74	143	0	3	25	0
8:15 AM	23	0	48	104	0	132	0	21	127	0	0	0	7	82	85	15	0	0	12	0	31	0	36	90	81	118	0	9	27	0
8:30 AM	60	0	11	118	7	55	0	15	54	0	0	0	9	123	85	0	0	0	13	0	26	7	52	126	85	31	0	0	11	0
8:45 AM	11	0	42	91	0	90	0	9	39	0	0	0	56	56	85	36	0	6	8	0	0	0	62	111	81	24	0	0	6	0
9:00 AM	4	0	0	70	0	89	0	6	55	0	0	0	0	55	85	0	0	0	7	0	0	0	0	16	85	0	0	0	3	0
9:15 AM	0	0	7	53	0	11	0	0	0	0	0	0	38	0	85	0	0	0	0	0	0	0	14	27	85	0	0	0	0	0

Figure 37 shows a graph of total corridor travel time, and Figure 38 shows a graph of total delay for I-20 from 6 a.m. to 6 p.m. These graphs show that metering increased both total travel time and delay compared to the no metering case. For metering with queue flush, these increases were marginal. However, the increases for strict metering were significant. Examination of main-lane speeds upstream and downstream of ramp merge areas show that the speeds for the three scenarios have minor differences, but these differences were not significant. This means that the entrance ramps are not the likely cause of congestion in this corridor.

Table 15 and Table 16 show queue flush statistics for the 6 meters in each direction. In the EB direction, almost all meters flushed some at one point or another during the day, but queue flushing at only one ramp (Great SW Parkway) was significant enough to affect the freeway during metering with queue flush operation. However, all these instances contributed to increased ramp delay under the strict metering strategy. In the WB direction, instances of flushing were fewer, but one ramp had significant flushing to make both metering scenarios ineffective at this ramp.
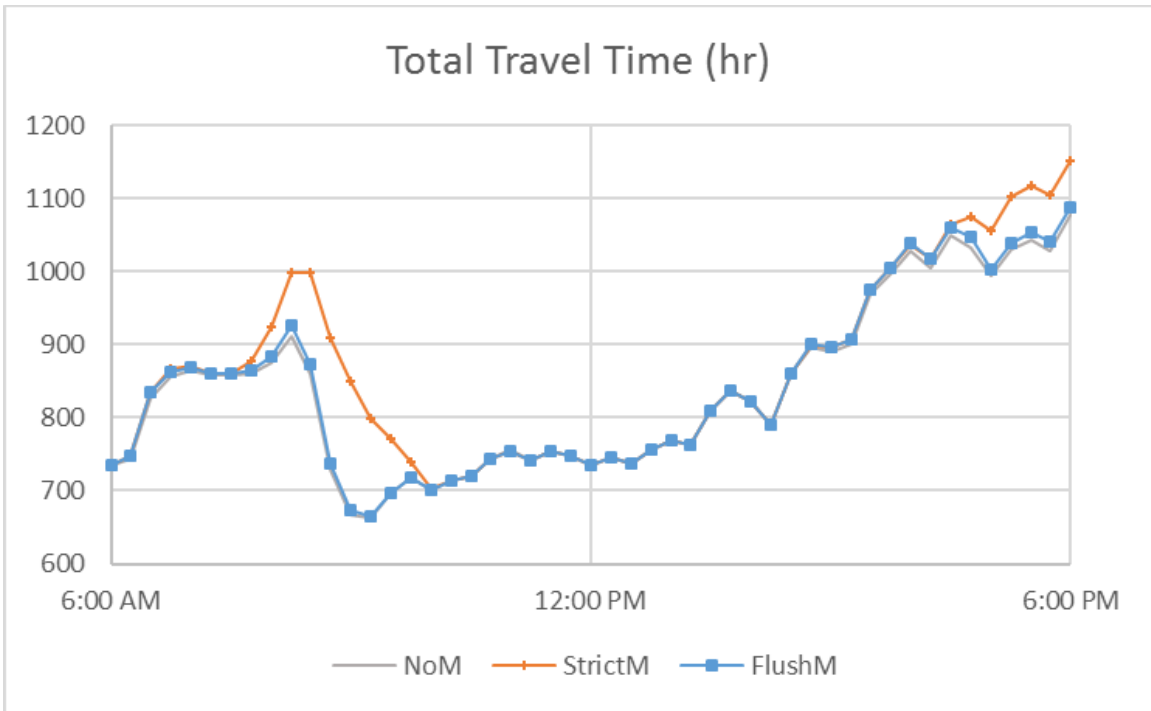
Figure 37. Total Travel Time for I-20 Corridor.
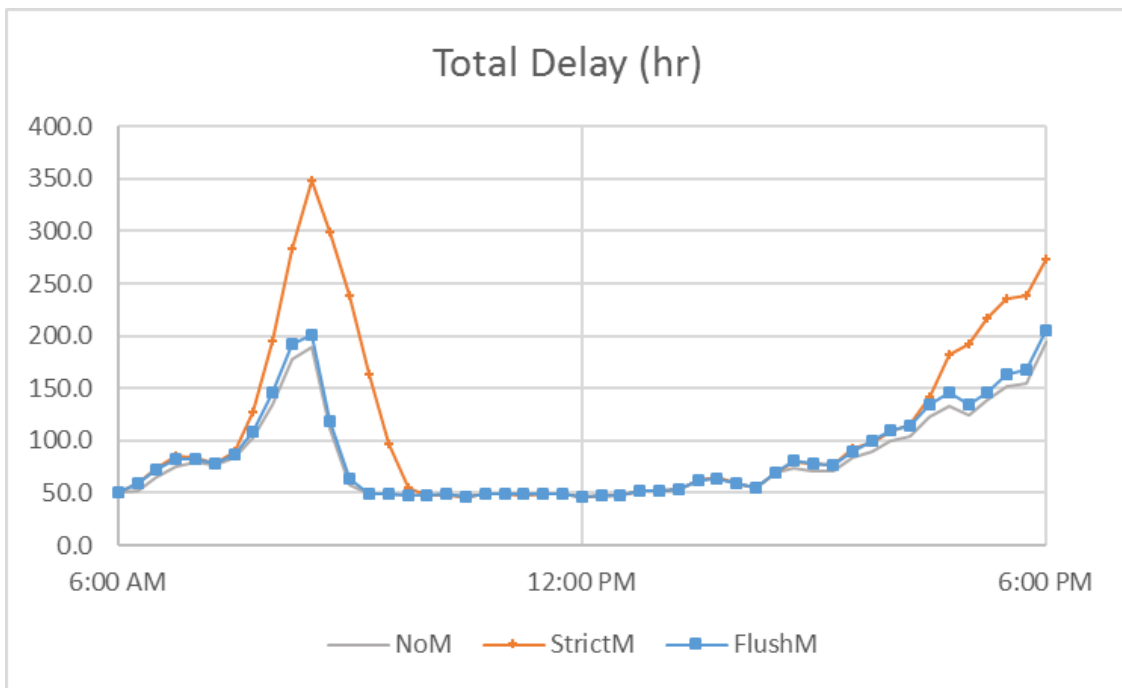
Figure 38. Total Delay for I-20 Corridor.

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Table 15. Queue Flush Data for EB I-20 (Percent of Hour).

Hour	Matlock Rd	S Collins St	Great SW Pkwy	Lake Ridge Pkwy	S Carrier Pkwy	Belt Line Rd
7	0.0%	0.0%	1.9%	0.0%	1.3%	0.3%
8	0.3%	0.0%	15.9%	0.3%	6.7%	0.0%
9	0.5%	0.0%	17.0%	0.0%	0.9%	0.2%
15	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%
16	3.6%	0.4%	0.0%	0.3%	0.0%	0.0%
17	3.4%	1.6%	0.1%	0.0%	0.0%	0.8%
18	6.1%	0.1%	0.0%	0.0%	2.1%	1.0%

Table 16. Queue Flush Data for WB I-20 (Percent of Hour).

Hour	Belt Line Rd	S Carrier Pkwy	Lake Ridge Pkwy	Great SW Pkwy	SH 360	S Collins St
7	0.0%	0.0%	0.0%	0.0%	0.0%	4.4%
8	0.0%	0.0%	0.0%	0.2%	0.0%	1.3%
9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%
16	0.0%	0.0%	1.3%	0.0%	0.0%	1.7%
17	0.0%	0.0%	0.6%	0.0%	33.2%	5.6%
18	0.0%	0.0%	1.0%	0.0%	25.8%	0.8%

Traffic performance data for US 75 shows that metering with queue flush operation improves freeway flow along southbound direction without significantly degrading operation of surface streets. For I-20 however, none of the two metering strategies provided any improvement to freeway lanes or the corridor. The likely reasons for this result seem to be that the metered entrance ramps are not the primary cause of congestion in the I-20 corridor. In this corridor, congestion appears to be because of several unmetered freeway-to-freeway (F2F) ramps feeding traffic to I-20 main lanes and F2F traffic from I-20, especially to SH 360.

Emissions

Figure 39 and Figure 40 provide results of emissions analysis using 15-minute VISSIM link data for the two corridors. These graphs provide the following information on ramp metering along southbound direction of US 75:

- Both metering scenarios reduced emissions for freeway vehicles. Reductions due to strict metering are more than metering with queue flush operation.
- Under strict metering, NOx emissions for all links increased by 0.3 percent. For this scenario, emissions of all other pollutants also increased, but these increases are below 0.85 percent.
- Under metering with queue-flush operation, there is a negligible increase in NOx and other pollutants, but all these increases are below 0.1 percent.

Figure 39. Emissions Estimates for US 75 Microscopic Simulations.

Emissions analysis of metering scenarios for I-20 corridor provides the following results:

- For freeway links, both metering scenarios resulted in a negligible decrease in NOx emissions. However, emissions of all other pollutants increased. These increases are less than 0.3 percent for strict metering and less than 0.2 percent for metering with queue-flush.
- For the entire corridor, both metering scenarios increased emissions of all pollutants. However, the increase in NOx emissions is negligible for metering with queue flush operation.
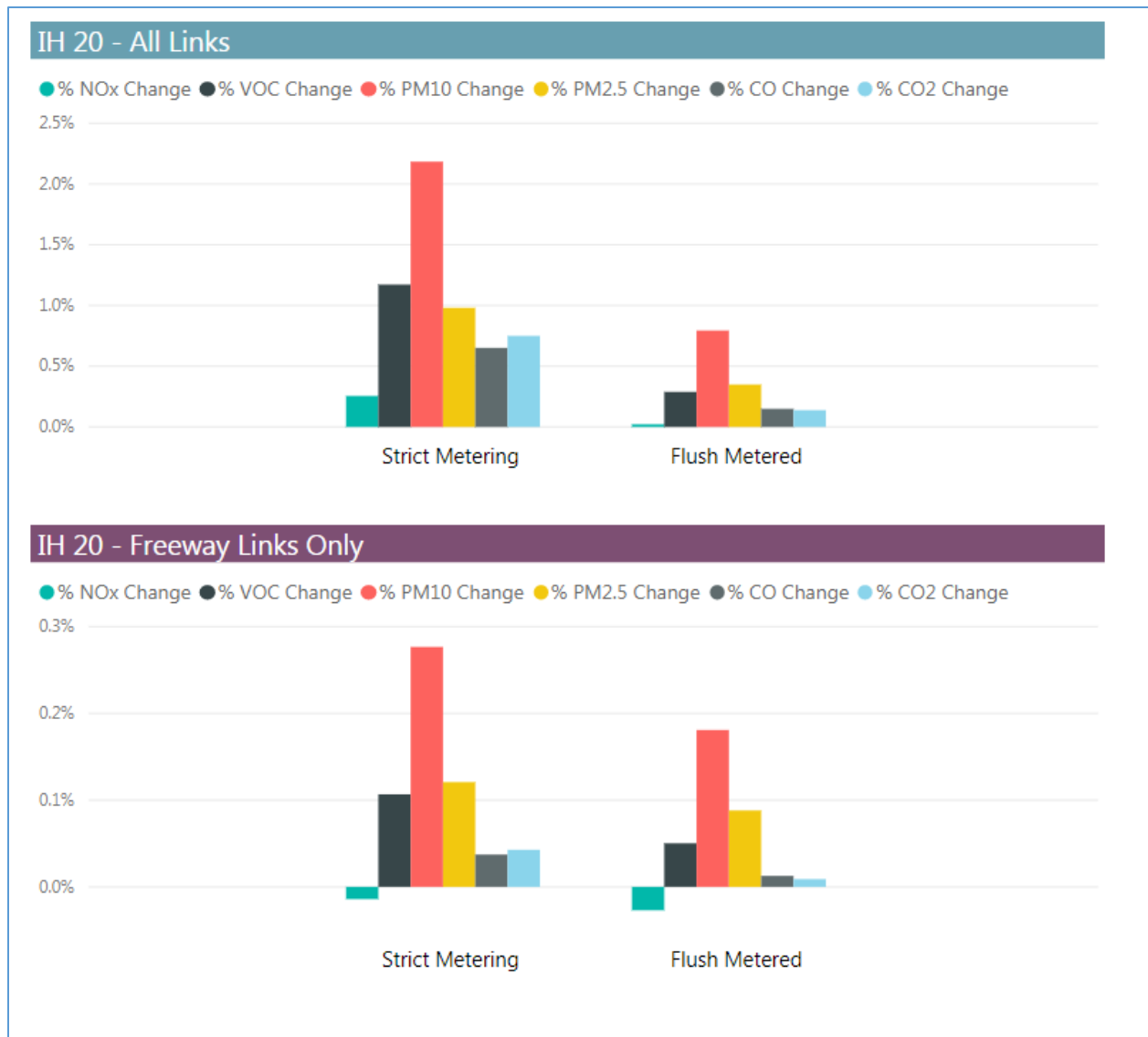
**Figure 40. Emissions Estimates for I-20 Microscopic Simulations.**

Emissions analysis reveals that in the absence of any diversion, metering with queue flush operation is better than strict metering. This strategy is also likely to have the least impact on NOx emissions for cases (US 75 in this case) where metering improves freeway operation without significantly degrading the overall operation of freeway and adjacent surface street roads.

EMISSIONS EVALUATION OF FIELD DATA

Figure 41 shows the resulting OpMode distributions from the field data. Researchers used these distributions as an input to the MOVES model to determine the potential emissions differences from ramp activities as a result of metering. The MOVES results indicated that on average the NOx emission rate (g/s) for a metered ramp is approximately 2.5 times higher than an unmetered ramp as shown in Figure 42.

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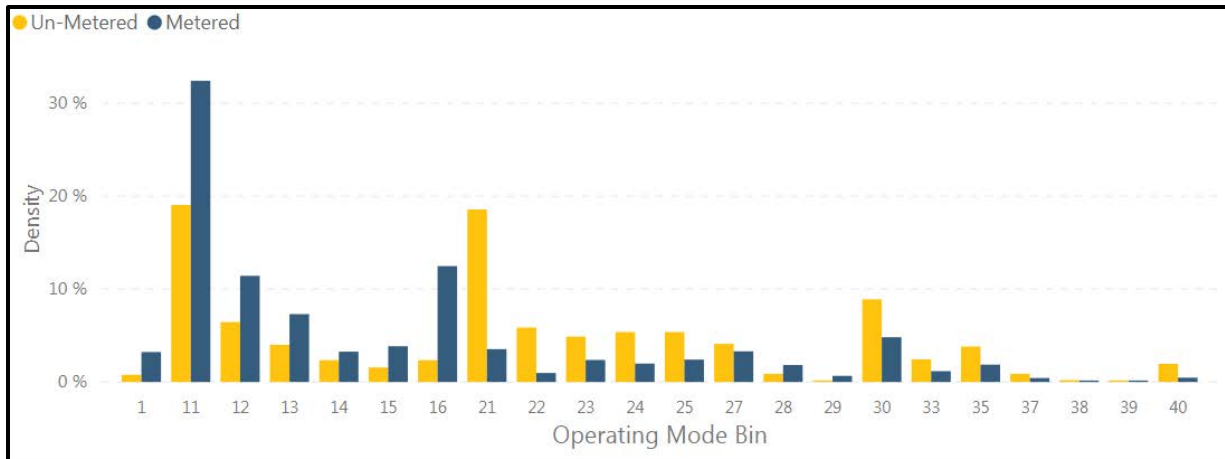
Figure 41. OpMode Distribution before and after Ramp Metering.
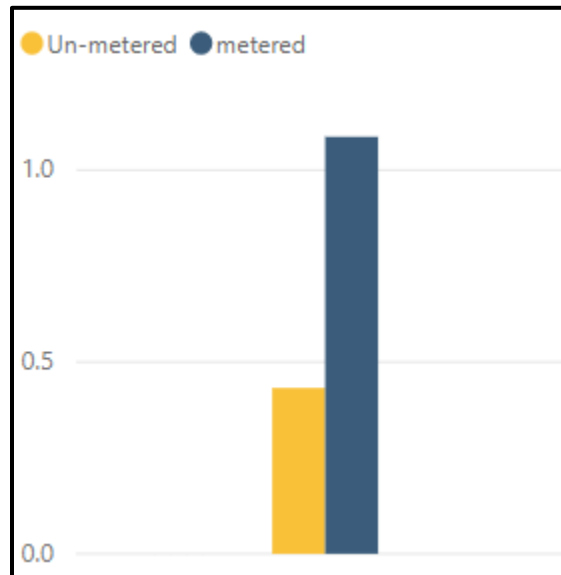
Figure 42. NO$_x$ Emissions before and after Ramp Metering.

BENEFITS AND COSTS OF RAMP METERING

Using DynusT results from the UE case, researchers calculated monetary savings associated with reductions in delay, fuel consumption, and NOx due to ramp metering. For these calculations, researchers used the following data (*76, 77*).

- Vehicle occupancy of 1.14.
- Gasoline cost of $2.50 per gallon.
- Diesel cost of $ 2.75 per gallon.
- Loss of time cost of $17.81 per person-hour.
- Cost of one ton of NOx of $15,000.

Table 17 through Table 21 provide results of this analysis. Here, negative dollar values represent savings and positive dollar values represent increased costs.

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Table 17. Daily Savings for UE Scenario (Freeway).

Corridor	Delay	Gasoline	Diesel	NOx	Total
I-20 Micro	−$70,182.76	−$1,385.00	$825.00	$433.00	−$70,309.76
I-20 EB Meso	−$52,595.96	−$2,202.50	$770.00	$318.00	−$53,710.46
I-20 WB Meso	−$22,929.98	−$5,425.00	$1,804.00	$805.00	−$25,745.98
US 75 Micro	−$21,261.72	−$2,007.50	−$379.50	−$156.00	−$23,804.72
US 75 Meso	−$44,965.26	−$2,350.00	−$1,614.25	−$399.00	−$49,328.51

Table 18. Daily Savings for UE Scenario (One-Mile Buffer).

Corridor	Delay Savings	Gasoline	Diesel	NOx	Total
I-20 Micro	−$90,293.62	−$4,390.00	$827.75	$322.00	−$93,533.87
I-20 EB Meso	−$78,060.82	−$1,840.00	$1,815.00	$774.00	−$77,311.82
I-20 WB Meso	−$81,218.00	−$2,082.50	$1,900.25	$796.00	−$80,604.25
US 75 Micro	−$75,015.65	−$6,912.50	−$1,743.50	−$643.00	−$84,314.65
US 75 Meso	−$135,134.02	−$11,352.50	−$2,224.75	−$793.00	−$149,504.27

Table 19. Daily Savings for UE Scenario (Two-Mile Buffer).

Corridor	Delay	Gasoline	Diesel	NOx	Total
I-20 Micro	−$100,094.41	−$5,372.50	$943.25	$339.00	−$104,184.66
I-20 EB Meso	−$85,615.04	−$4,210.00	$1,452.00	$561.00	−$87,812.04
I-20 WB Meso	−$77,996.19	−$3,822.50	$1,542.75	$581.00	−$79,694.94
US 75 Micro	−$150,394.05	−$12,097.50	−$2,714.25	−$1,010.00	−$166,215.80
US 75 Meso	−$156,385.58	−$13,555.00	−$2,241.25	−$901.00	−$173,082.83

Table 20. Daily Savings for UE Scenario (Three-Mile Buffer).

Corridor	Delay	Gasoline	Diesel	NOx	Total
I-20 Micro	−$104,776.03	−$6,415.00	$789.25	$275.00	−$110,126.78
I-20 EB Meso	−$74,924.28	−$5,037.50	$1,028.50	$378.00	−$78,555.28
I-20 WB Meso	−$91,725.35	−$6,742.50	$709.50	$220.00	−$97,538.35
US 75 Micro	−$190,805.94	−$15,475.00	−$3,390.75	−$1,270.00	−$210,941.69
US 75 Meso	−$180,671.84	−$16,280.00	−$2,530.00	−$1,080.00	−$200,561.84

Table 21. Daily Savings for UE Scenario (Four-Mile Buffer).

Corridor	Delay	Gasoline	Diesel	NOx	Total
I-20 Micro	−$100,635.49	−$7,520.00	$200.75	$35.00	−$107,919.74
I-20 EB Meso	−$68,677.94	−$5,742.50	$929.50	$307.00	−$73,183.94
I-20 WB Meso	−$87,516.45	−$7,622.50	$514.25	$117.00	−$94,507.70
US 75 Micro	−$203,277.98	−$7,107.50	−$3,610.75	−$136.30	−$214,132.53
US 75 Meso	−$207,216.84	−$19,727.50	−$2,835.25	−$128.00	−$229,907.59

These calculations provide conservative estimates because they use lower vehicle occupancy value of 1.14 for all vehicles. Typically, researchers use occupancy values 1.25 and 1.14 for vehicles and trucks, respectively, in such analyses. These calculations also ignore the suggested $53.59/hr cost of delay to trucks (76).

Note that metering produces an increase in costs associated with diesel and NOx for all I-20 scenarios. These increases can be attributed to the increase in truck VMT predicted by the model. What this means is that improvements produced by ramp metering along I-20 freeway mainlines attracted more trucks from other routes.

The last columns in the above tables provide daily savings due to ramp metering. Yearly savings can be calculated by multiplying daily savings by 260 (52 weeks/year and 5 days/week). As an example, estimated yearly savings for US 75 micro corridor freeway will be $6,189,227.

SUMMARY OF FINDINGS AND GENERAL GUIDELINES

By design, a ramp meter converts free-flow operation of ramp vehicles to a stop-and-go operation and increases delay, fuel consumption, and emissions. It also puts a cap of 900 vehicles/hour on ramp capacity. Depending on ramp demand and the nature of ramp metering strategy, a meter may also adversely impact adjacent and upstream facilities. Examples of these are a blocked frontage road lane or a blocked upstream intersection. Thus, installing and operating a ramp meter only makes sense if the resulting benefits to freeway operations outweigh any adverse impacts on adjacent surface streets. This requires a careful study to determine not only where a ramp meter could be installed, but also when it should be operated.

This research used computer simulation models to assess the use of ramp metering for mitigating freeway congestion. The research also studied potential air quality impacts of ramp metering. Results of detailed simulation analysis shows that ramp metering with flush operations is the best strategy for mitigating freeway congestion in situations where on-ramp vehicles are the major contributors to congestion and ramp demand is lower than meter capacity. Under conducive traffic conditions, and in presence of good ramp geometry, this strategy improves freeway operations without major degradation to surface-street traffic operations. This strategy also has the least amount of negative environmental impacts, especially on NOx emissions. Additional economic analysis shows that any monetary cost associated with resulting increases in emissions is negligible as compared to traffic operations improvements when the corridor for ramp metering is selected judicially. This research confirmed that speed-based heat-maps are useful tools for identifying the severity and extent of recurring congestion in corridors and can be used

to identify if metering could be beneficial by studying geometric and traffic flow characteristics of the corridor.

Success of ramp metering also requires adherence to the following guidelines:

- Any merge-related geometric issues must be addressed before considering metering a ramp.
- Meter should not be installed at a ramp with sustained demand higher the meter capacity. Short term hourly flow rate calculated using 5-minute volume can be used to assess level of platooning in vehicles arriving at a ramp. Generally, storage distance of at least 400 ft should be provided to handle higher cyclic vehicle arrival rates. The capacity of a single-lane, one-car-per-green meter is 900 vph. Dual-lane metering, a case not considered in this project, can provide ramp capacities of up to 1700 vph. Providing dual-lane metering generally requires significant additional civil costs associated with ramp widening.
- Strict metering should not be used because it can cause blocking of adjacent or upstream intersections. Strict metering is also unpopular with both drivers and cities, both of whom must be on board when implement ramp metering.
- Metering conventional ramps should only be considered for cases where congestion, either in the merge areas, or downstream, is caused by merging traffic from these ramps. Ramp metering cannot mitigate freeway congestion caused by slowing or weaving of exiting vehicles (i.e., at F2F ramps) or other exit-related capacity issues.
- Ramp metering can also be ineffective where a high percent of traffic entering the freeway is from uncontrolled or ineffective ramps. Examples of such ramps include F2F ramps and surface-street-to-freeway ramps with demand more than the capacity of a meter.

RECOMMENDATIONS

Based on the findings of computer simulation and emissions modeling, researchers recommend considering the use of ramp metering with flush operation in the US 75 corridor studied. This freeway segment is suitable for an initial ramp metering system because:

- Corridor size is sufficiently long for providing a meaningful system with a better likelihood of user and partner support.
- The corridor has continuous frontage roads.
- Both mesoscopic and microscopic models predict improvements along the corridor.
- There are no F2F ramps within the proposed corridor limits.
- There is no significant adverse impact of ramp metering on air quality in this corridor.

Appendix E provides benefit-cost analysis related to this recommendation. These calculations show net present value and benefit-to-cost ratio of $31,910,607 and 18:1, respectively.

This research used computer models to study impacts of ramp metering on traffic operations and air quality in two congested freeway corridors. Because computer models are simplistic representations of reality, these results should be treated with caution and as an indication of trends rather than absolute numbers.

NEXT STEPS

If TxDOT and NCTCOG wish to move forward with the above recommendation, the following steps will be needed:

1. With the assistance of researchers, share the results of this project internally within TxDOT and NCTCOG to solicit support from within and between departments in the two agencies.
2. Identify a funding mechanism (funding level and source) for carrying out required next step. The support may come from traditional TxDOT implementation program, from interagency funds, or other outside sources. This funding is needed for:
   a. Data collection to evaluate current traffic conditions, specifically freeway and ramp volumes in the US 75 corridor.
   b. Survey of the corridor to evaluate and document geometric conditions. Data to be collected include:
      i. Potential locations for installing signals, cabinets, sensors, etc.
      ii. Survey of existing ITS infrastructure to which meter could be connected to.
      iii. Distance measurements to assess acceleration and storage requirement.
      iv. Identification of power sources for field equipment.
   c. Evaluate geometric and traffic warrants using criteria provided in Appendix A.
   d. Develop a plan for conducting a public campaign.
3. Identify all hardware and software components needed to implement recommended ramp metering and assess costs of these components. HOU is currently testing a new ramp controller. HOU also has design sheets for placements of signals, sensors, and other hardware to support ramp metering. Appendix B illustrates these sheets and can be obtained by contacting HOU.
4. Identify funding sources and funding levels to support routine operation and maintenance of the system in the future. Specifically, identified funding should provide for supporting staff dedicated to ramp meters with specific assigned duties. Even if funds are available to move forward to the installation stage, ramp metering should not be implemented without a plan to acquire funds necessary for future maintenance and operations of the system.

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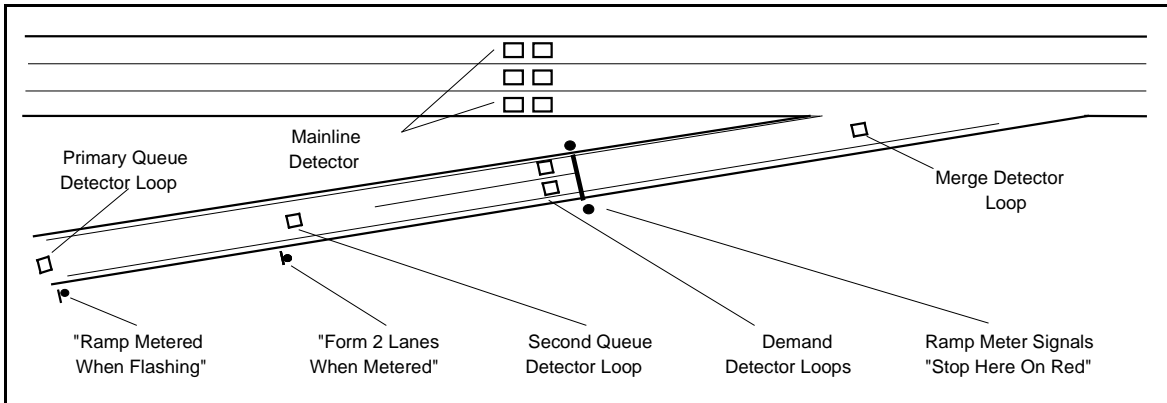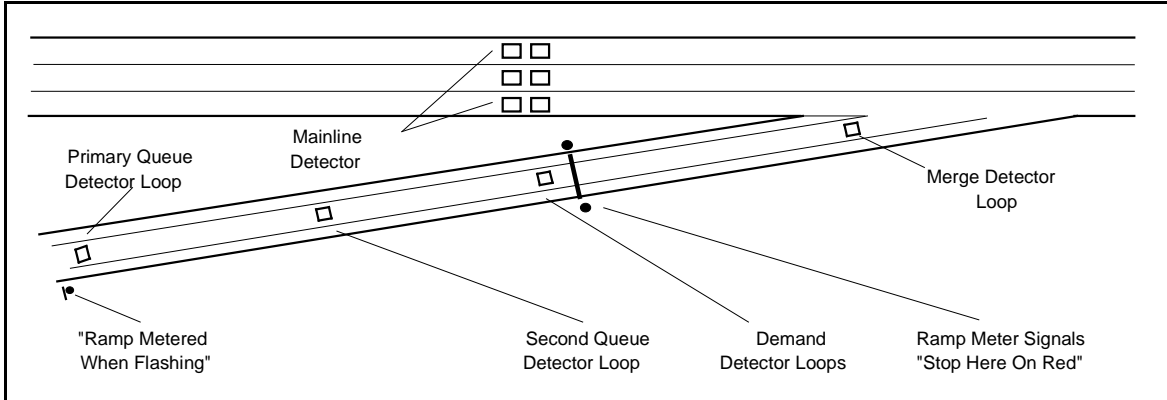
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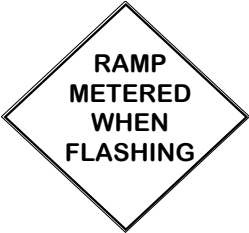76. Analysis Procedures and Mobility Performance Measures: 100 Most Congested Texas Road Sections, Technical Memorandum, TTI, August 2017; Accessed at: https://static.tti.tamu.edu/tti.tamu.edu/documents/TTI-2017-8.pdf
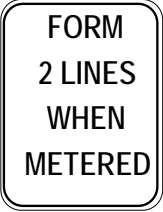77. Gas Buddy. Accessed at: https://www.gasbuddy.com/home?search=Dallas&fuel=1.

APPENDIX A: TXDOT RAMP METER COMPONENTS AND DESIGN DETAILS

Layout of Components for Single and Dual-Lane Meter

Primary Queue
Detector Loop

Mainline
Detector

Merge Detector
Loop

"Ramp Metered
When Flashing"

Second Queue
Detector Loop

Demand
Detector Loops

Ramp Meter Signals
"Stop Here On Red"

Primary Queue
Detector Loop

Mainline
Detector

Merge Detector
Loop

"Ramp Metered
When Flashing"

"Form 2 Lanes
When Metered"

Second Queue
Detector Loop

Demand
Detector Loops

Ramp Meter Signals
"Stop Here On Red"

| Placement and Application of Ramp-Meter Detectors		
Type of Detector	**Location/Size**	**Application**
Mainline (Optional)	Located in the freeway upstream and/or downstream of the on-ramp ingress point to the freeway.	Provides freeway occupancy, speed, or volume information that is used to select the local metering rate. These detectors also provide incident detection measurement devices for traffic management centers. Used by nearly all agencies.
Merge (Optional)	Placed upstream of the merge area and downstream of the stop-bar along the on-ramp.	Used primarily to provide on-ramp count data. Minnesota uses it to determine the appropriate time to terminate metering based on the differential between the current on-ramp volume and the fixed-time metering rate.
Passage (Optional)	Positioned immediately downstream of the stop-bar.	Used in California and Washington to determine the duration of the green signal display on the specified lane.
Demand (Required)	Placed immediately upstream of the stop-bar in both specified lanes.	Senses vehicle presence at the stop-bar and initiates the green traffic signal display for that specific lane under the selected metering strategy.
Second Queue (Optional)	Placed approximately half-way between the stop-bar and the on-ramp entrance point in both lanes.	Incrementally increases the metering rate to control growing queues within the queue storage reservoir.
Primary Queue (Required)	Positioned near the on-ramp entrance area (typically within 30 meters).	Monitors excessive queues that cannot be contained within the queue storage reservoir. Maximizes the metering discharge rate to clear excessive queues.

| Ramp Metering Signing Locations and Applications		
Sign	**Location**	**Application**
RAMP METERED WHEN FLASHING (diamond warning sign)	Placed on the left side of the frontage road approximately 200 ft (60 m) upstream of the slip-ramp entrance point and downstream of any signalized intersections or off-ramps.	This warning sign is accompanied by a yellow flashing beacon that is activated during metered periods to alert motorists of the upcoming controlled ramp.
FORM 2 LINES WHEN METERED	Positioned near the beginning of the dual-lane queue storage reservoir on the right side of the on-ramp.	This regulatory sign is used to convert the single-lane on-ramp into a dual-lane queue storage reservoir during flow signal operations.
STOP HERE ON RED (with arrow)	Placed on both sides of the on-ramp at the flow signal stop-bar. This sign is placed on the signal pole under the post-mounted configuration.	This regulatory sign identifies the flow signal stop-bar location and is used to align drivers over the demand detectors placed upstream of the stop-bar.
ONE VEHICLE PER GREEN	Can be optionally placed either on the signal pole or with the "Stop Here On Red" regulatory sign under a mast-arm configuration.	This regulatory sign is used to inform motorists of the intended traffic control under flow signal operations. An appropriate sign should be posted for platoon or bulk metering.
RIGHT LANE RIGHT SIGNAL	Placed with the corresponding signal head under the mast-arm design.	This regulatory sign is used to identify the proper lane control and inform motorists of the traffic control requirements during metered periods.
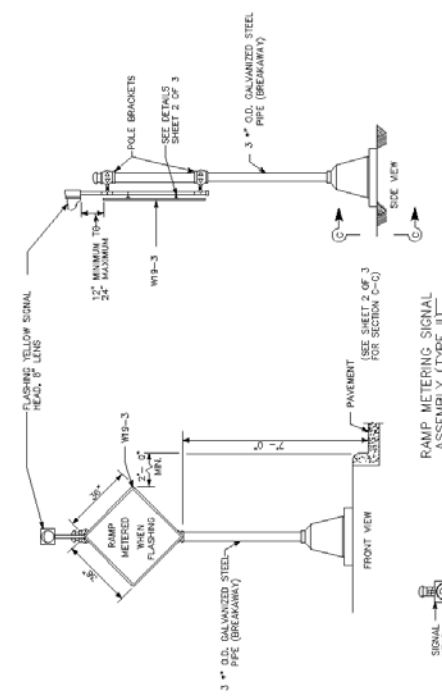
RAMP METERING SIGNAL ASSEMBLY (TYPE II)

NOTES:

1. BANDING TYPE POLE FITTINGS WILL NOT BE ACCEPTABLE.

2. CONDUIT TERMINATING IN PEDESTAL BASES SHALL EXTEND VERTICALLY APPROXIMATELY TWO (2) INCHES ABOVE THE CONCRETE FOUNDATIONS.

3. ALL STRUCTURAL STEEL, NUTS, BOLTS, WASHERS, AND BRACKETS SHALL BE GALVANIZED AS PER ITEM 442 EXCEPT AS NOTED.

4. THE ALPHABET & LATERAL SPACING BETWEEN LETTERS & NUMERALS SHALL CONFORM WITH THE FEDERAL HIGHWAY ADMINISTRATION'S "MANUAL ON UNIFORM TRAFFIC CONTROL DEVICES FOR STREETS AND HIGHWAYS" LATEST EDITION AND ANY CHANGES THERETO. LATERAL SPACING OF TEXT SHALL BE SUCH AS TO PROVIDE A BALANCED APPEARANCE. THE SIGN BACKGROUND SHALL BE FLAT SURFACE REFLECTIVE SHEETING CONFORMING TO DEPARTMENTAL MATERIALS SPECIFICATION D9-8300. THE ALUMINUM SIGN BLANKS SHALL CONFORM TO ITEM (TYPE A). THE ALUMINUM SIGN TYPE "A" SHALL CONFORM TO ITEM "PLYWOOD SIGN TYPE A".

5. THE CONTRACTOR SHALL SUPPLY QUICK-DISCONNECT CONNECTORS FOR CONDUCTORS TO THE RAMP METERING SIGNAL ASSEMBLIES AS APPROVED BY THE ENGINEER. THIS ITEM WILL NOT BE PAID FOR DIRECTLY BUT SHALL BE CONSIDERED AS INCIDENTAL TO RAMP METERING SIGNAL ASSEMBLIES OF THE VARIOUS TYPES.

6. SIGNAL LAMPS SHALL BE IN COMPLIANCE WITH TxDOT 1993 STANDARD SPECIFICATIONS ITEM 682.

7. STEEL PIPE SHALL BE 3" SCH. 40 (3" O.D.) STANDARD PIPE ASTM A53.
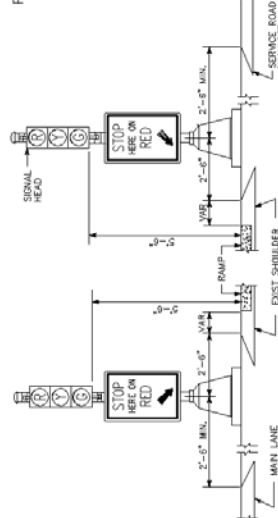
TYPICAL SECTION WITH SHOULDER
RAMP METERING SIGNAL ASSEMBLY (TYPE 1)
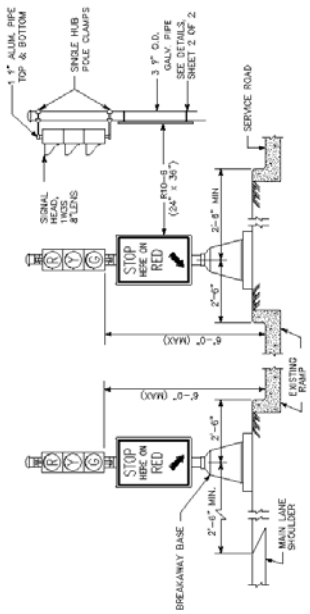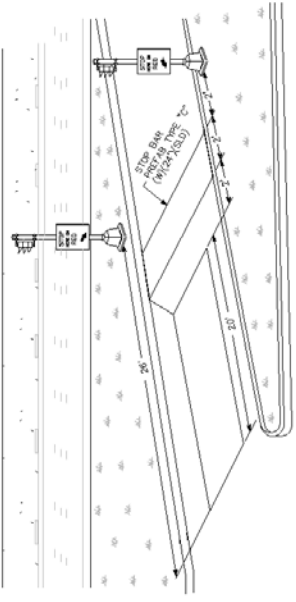
TYPICAL SECTION WITH CURB
RAMP METERING SIGNAL ASSEMBLY (TYPE 1)
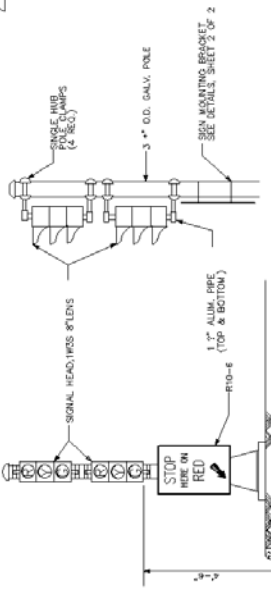
RAMP METERING ASSEMBLY (TYPE 1)
(FOR USE WHEN ASSEMBLY CAN ONLY BE PLACED ON ONE SIDE OF ENTRANCE RAMP)

102

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MERGE LOOP

120'-0"

FROM HEAD OF DEMAND LOOP
TO HEAD OF MERGE LOOP

RAMP METER
SIGNAL ASSEMBLY
TYPE I

RAMP METER
SIGNAL ASSEMBLY
TYPE I

SEE DETAIL A

DEMAND LOOP

DISTANCE VARIES

TYPICAL RAMP METER
SIGNAL INSTALLATION

TRAP LOOPS

RAMP METER
CONTROLLER

RAMP METER
SIGNAL ASSEMBLY
TYPE II

QUE LOOP

DETAIL A

120'-0"

FROM HEAD OF DEMAND LOOP
TO HEAD OF MERGE LOOP

STOP BAR
PREFAB TYPE "C"
(4"X24" SOLID)

20'

20'

DISTANCE VARIES
FROM RAMP METER TYPE I
TO RAMP METER TYPE II

104

APPENDIX B: TXDOT RAMP METERING CRITERIA

FREEWAY TRAFFIC CONDITIONS

Ramp metering is likely to result in higher freeway speeds if the average per lane 15-minute flow rate of the two right-most lanes is above the threshold provided in Figure B1.

Data needed to apply this criterion:

- Lane-by-lane 15-minute flow rates near the ramp for the time period under consideration.
- Measured or estimated acceleration distance.
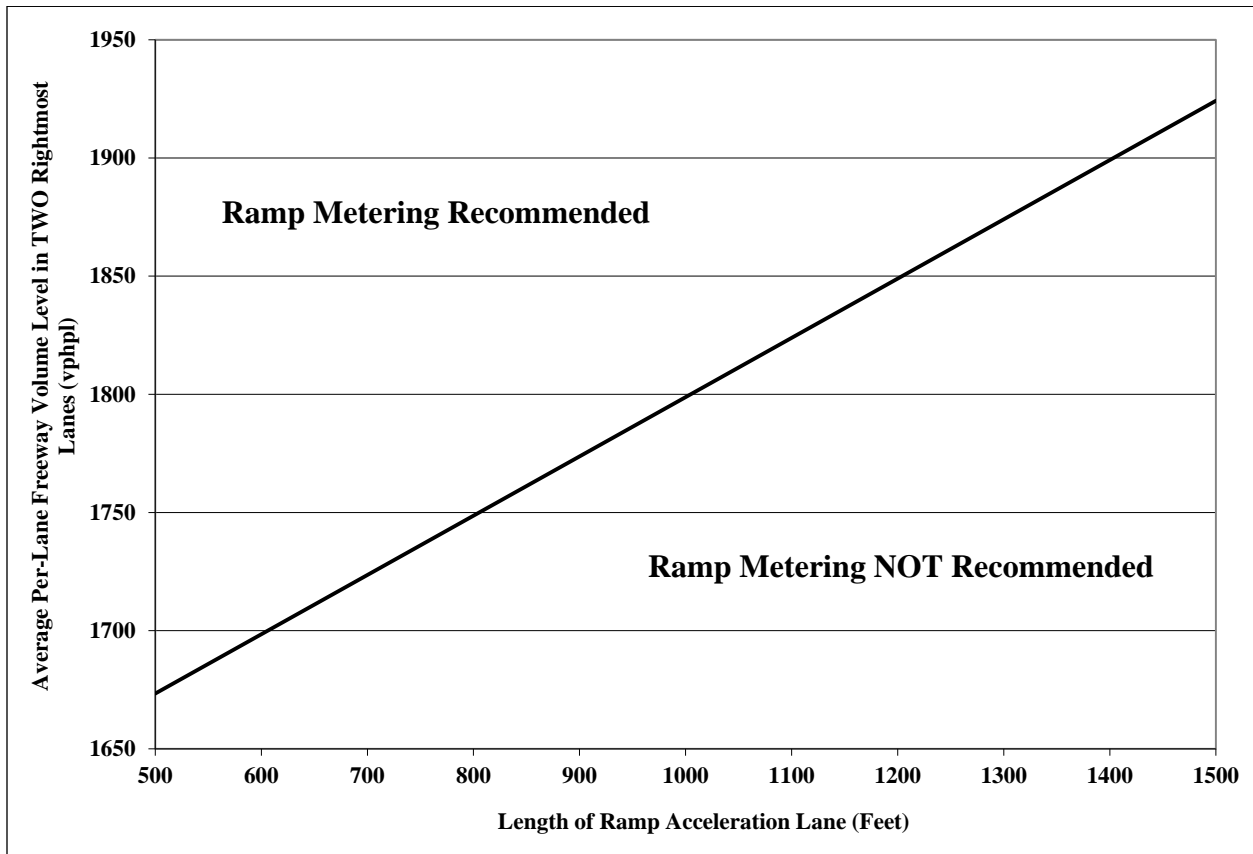
Figure B1. Freeway Main Lane Conditions.

FREEWAY PLUS ON-RAMP TRAFFIC CONDITIONS

Ramp metering is likely to result in higher freeway speeds if:

1. 15-minute ramp flow rate is more than 300 vph.
2. Combined 15-minute ramp plus right-most-freeway-lane is more than the threshold provided in Figure B2.

Data needed to apply this criterion include:

- 15-minute flow rate for the right-most freeway lane near the ramp during the time-period under consideration.
- 15-minute on-ramp flow rate.
- Measured or estimated acceleration distance.
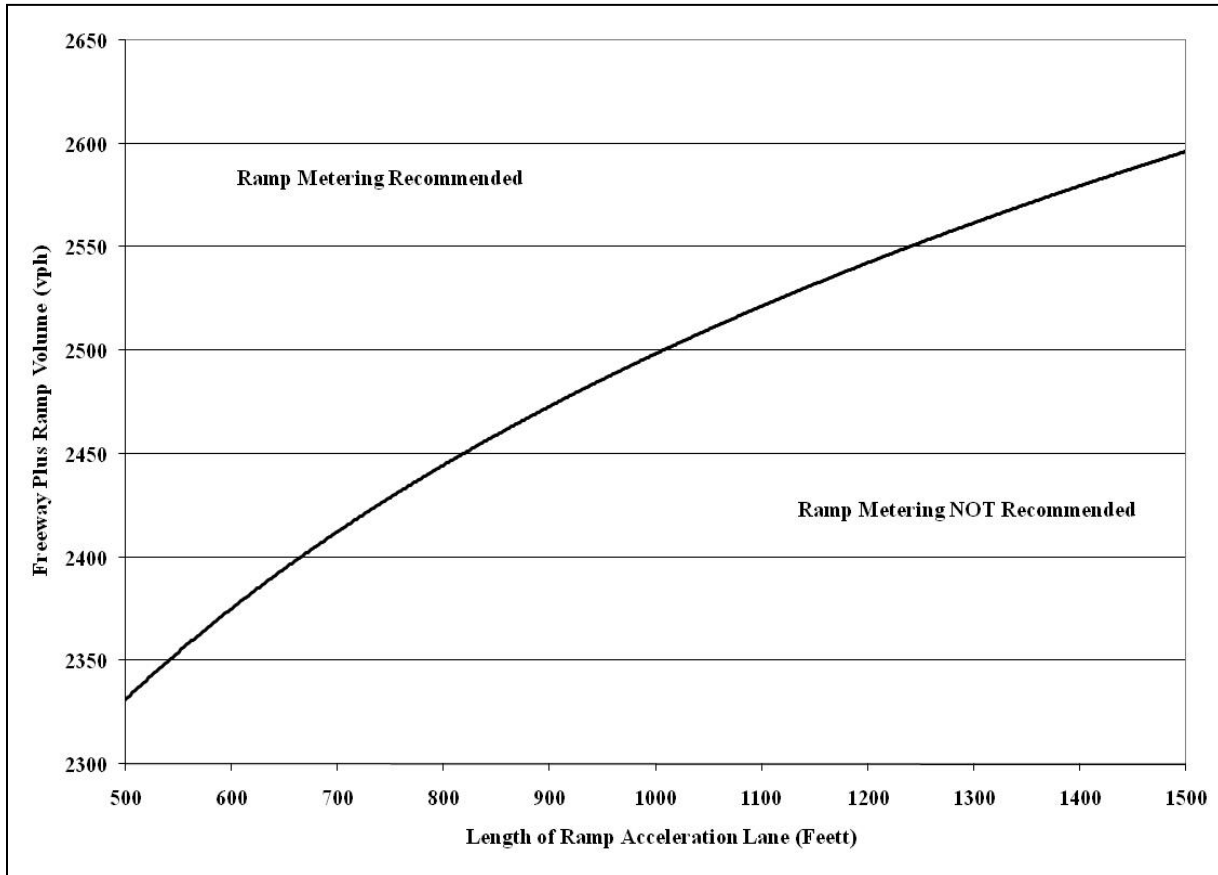
Figure B2. Freeway and Ramp Conditions.

ACCEPTABLE RAMP MERGE SPEEDS

Ramp metering implementation at a ramp requires adequate acceleration distance for stopped ramp vehicles to reach safe merge speeds. Data required for applying this criterion are:

- Measured or estimated acceleration distance.
- Ramp grade from stop line at the meter to merge location.
- Actual or estimated freeway speed in the merge area during the time-period under consideration.

To apply this criterion:

1. Use grade and acceleration distance to obtain estimated speed ramp vehicles at the merge point using Figure B3.
2. Using estimated speed from Step 1 and selected freeway speed to determine from Figure B4 if there is sufficient acceleration length to achieve desired headway. This figure provides for estimating minimum merge speed for three headway conditions: aggressive (1.5-sec. headway), average, and conservative (2-sec. headway) drivers.
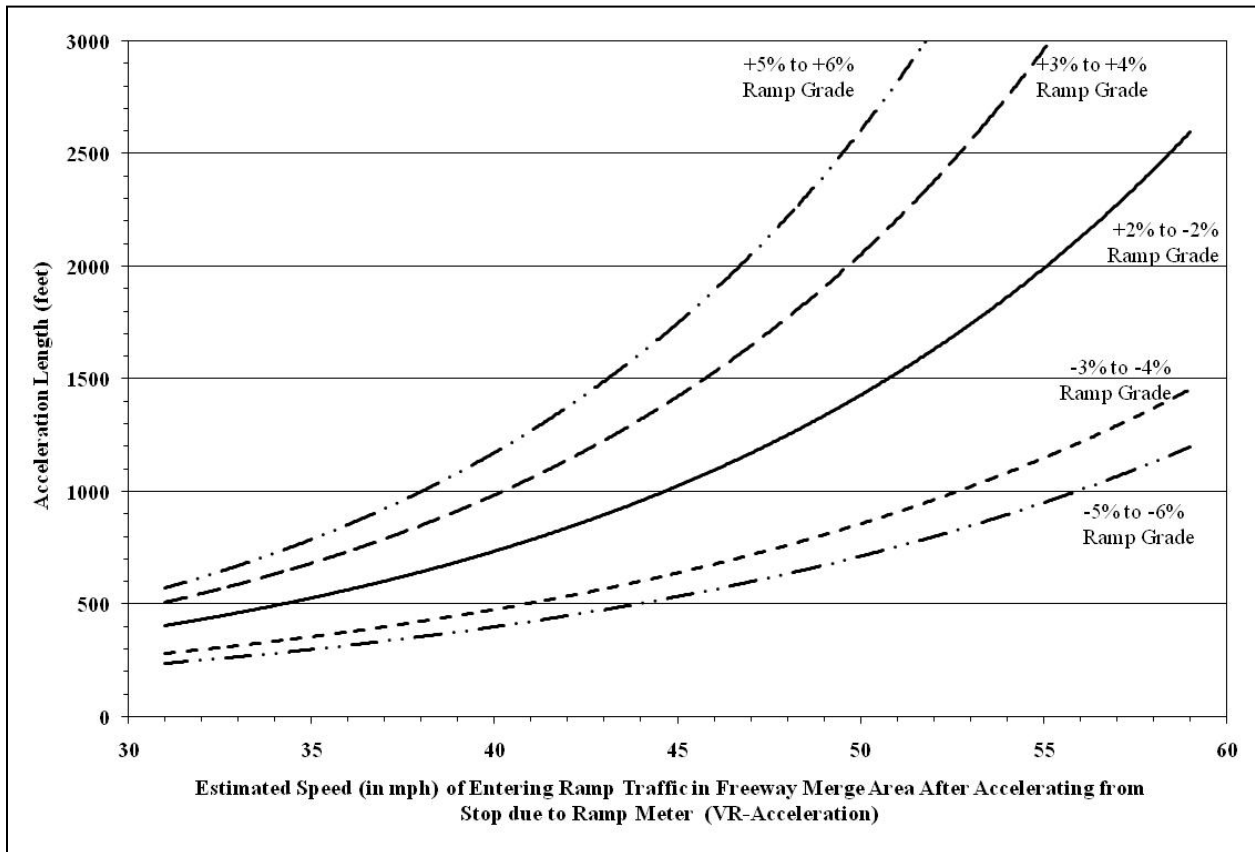
Figure B3. Estimated Speeds of Metered Vehicles at Merge Point.
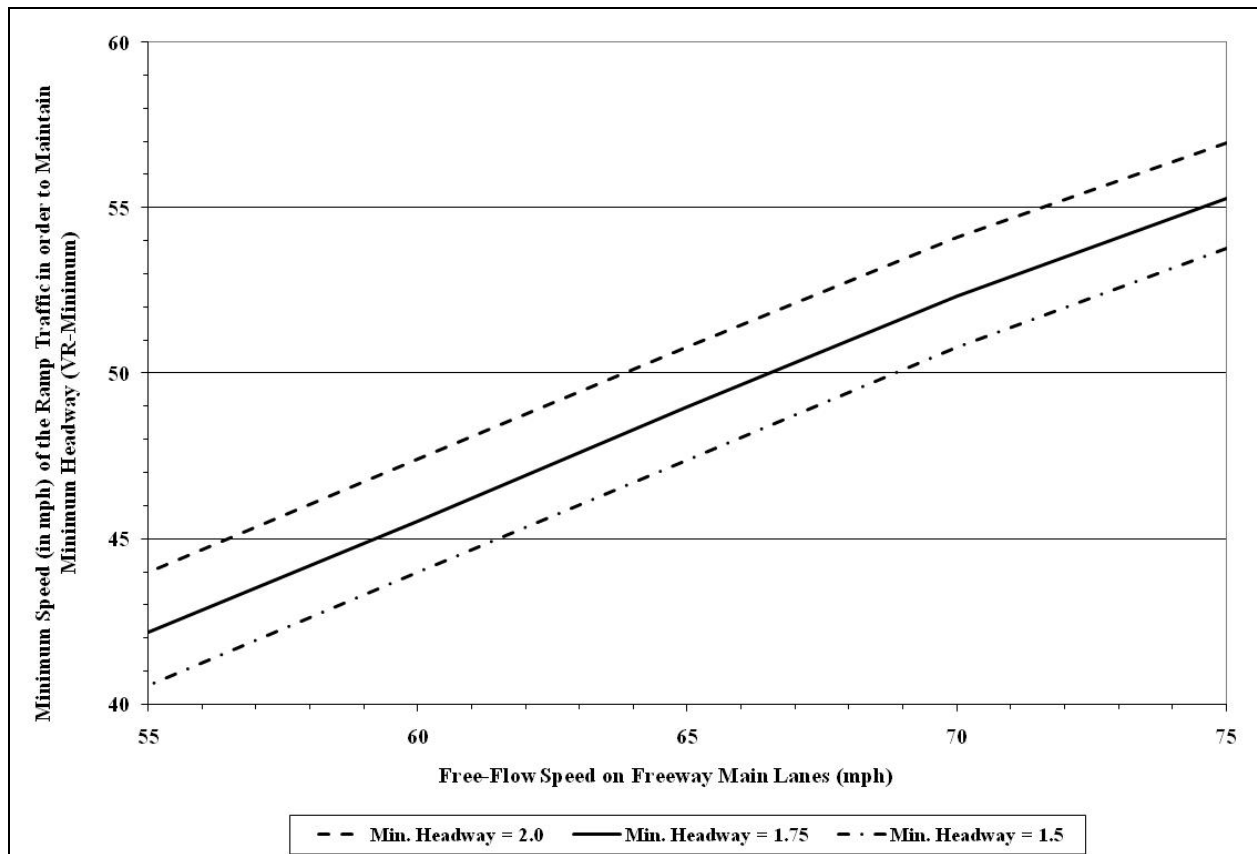
Figure B4. Minimum Speed of Ramp Vehicle to Maintain Minimum Headway between it and Main Lane Vehicles.

RAMP STORAGE REQUIREMENTS

Even when the ramp demand is lower than capacity of a ramp meter, effective ramp metering requires the availability of space to store cyclic demand arriving from upstream signal at higher rate. This is particularly true in Texas, where meter implementation uses a queue detector to prevent ramp queues form interfering with flow from an upstream intersection or an exit ramp. Figure B5 provides for storage length determination (distance from stop bar to queue detector) for two service times.

Data required for determining if sufficient storage length exists:

- Measured or estimated storage distance.
- 15-minute ramp flow rate.
- Desired service time.

To apply this criterion:

1. Use flow rate and desired service time to determine required storage length.
2. Determine if available storage length is equal or greater than required storage length.

108
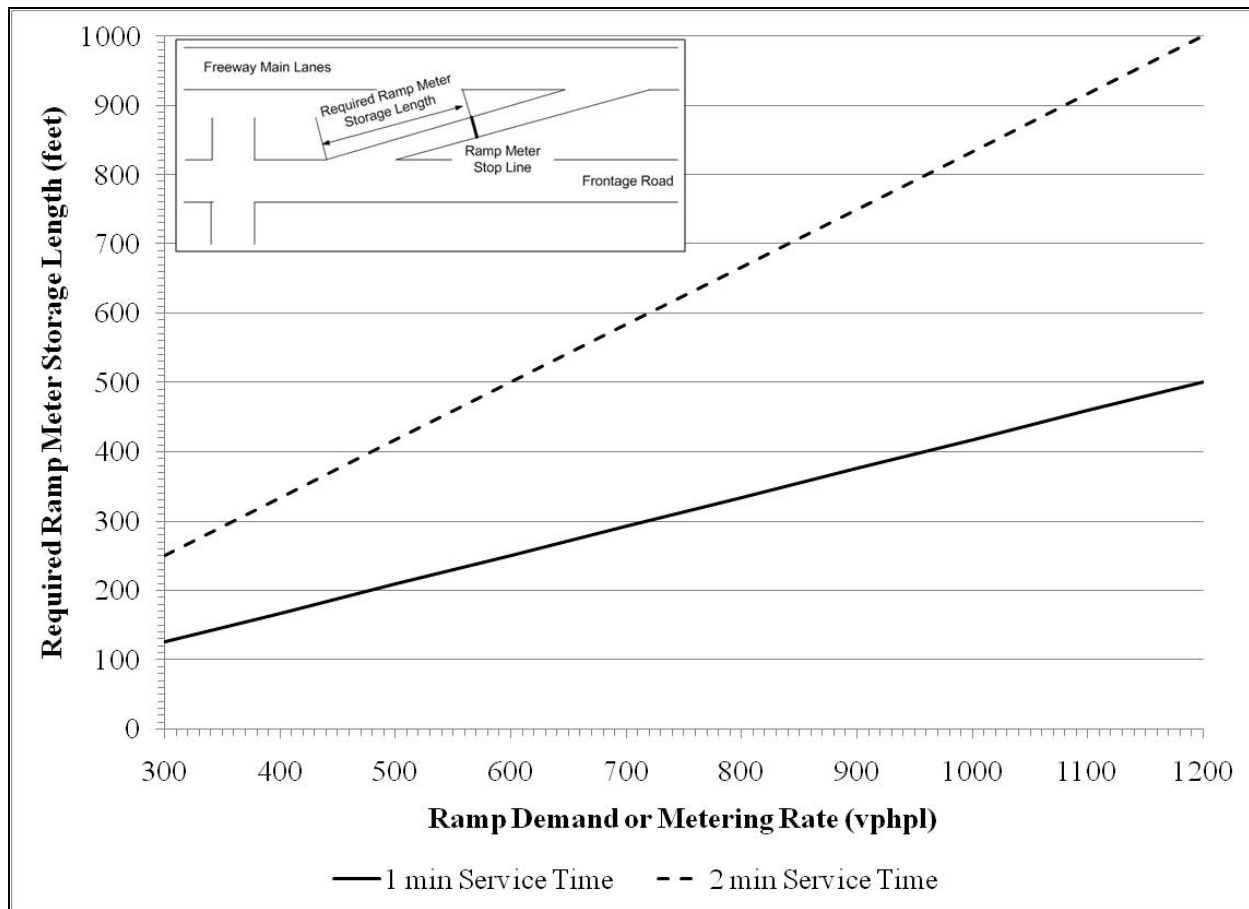
Figure B5. Storage Space Requirement.

The inset in Figure B5 illustrates storage length for a case where no auxiliary or added lane exists on the frontage road. In such a case, storage space is measured from upstream gore on frontage road to signal location on entrance ramp. In cases where an additional lane exists for direct ramp entry, moving the queue detector farther upstream can provide additional storage beyond ramp gore. This can be done as long as there is sufficient room to place the advance warning sign/flasher and there is appropriate sight distance from the upstream signal (or exit ramp in the case of an X-ramp configuration). Furthermore, pushing the stop bar as far downstream as possible can provide additional storage. However, two factors limit how far downstream the stop bar can move:

- Impact on acceleration distance.
- Lateral clearances for the signal pole.

SAFETY CONSIDERATIONS

Metering an entrance may be also appropriate at locations where a high frequency of crashes exist because of inadequate merge area. At such locations, ramp metering can improve safety if:

- Rate of freeway crashes in the immediate vicinity of ramp exceeds mean crash rate for comparable freeway sections in the metropolitan area.
- The primary cause of majority of these crashes can be attributed to traffic merging from the ramp (i.e., side-swipe crashes in the merge area, or rear-end crashes in the right-most lane upstream of the ramp merge).
- Sufficient acceleration and storage lengths exist.

OTHER CONSIDERATIONS

Other considerations to ensure effective ramp metering include:

- Capacity of a single-lane one-car-per-green is limited to less than 900 vph. Allowing multiple (two or three) cars to enter the freeway can increase the meter capacity to about 1100 vph. A single-lane meter should not be used if ramp demand is higher than the capacity of the selected strategy.
- Even when present, an isolated meter should not be activated unless freeway main lane speeds drop below 50 mph or freeway main lane average occupancy increase above 18 percent. However, a meter not meeting these conditions can be activated if it is part of a system of ramps and a downstream ramp meets activation criteria.
- Metering rate should be based on ramp demand.

APPENDIX C: US 75 DYNUST RUN ANALYSIS

Figure C1. US 75 Meso versus Micro Model Limits for 0-Mile Buffer.
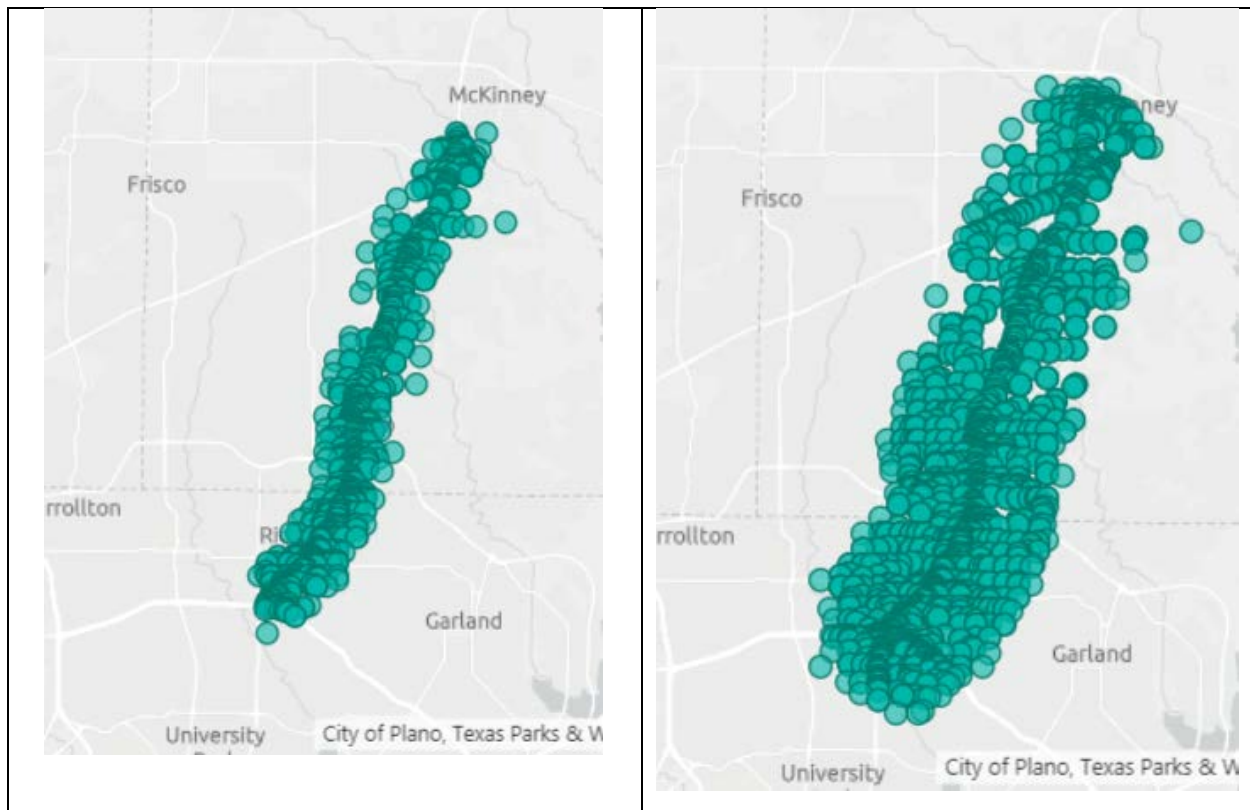
Figure C2. US 75 Corridor 1- and 3-Mile Buffer Sizes for Meso Model.

Buffer	One shot Run	UE
0 Mile		
1 Mile		
3 Mile		
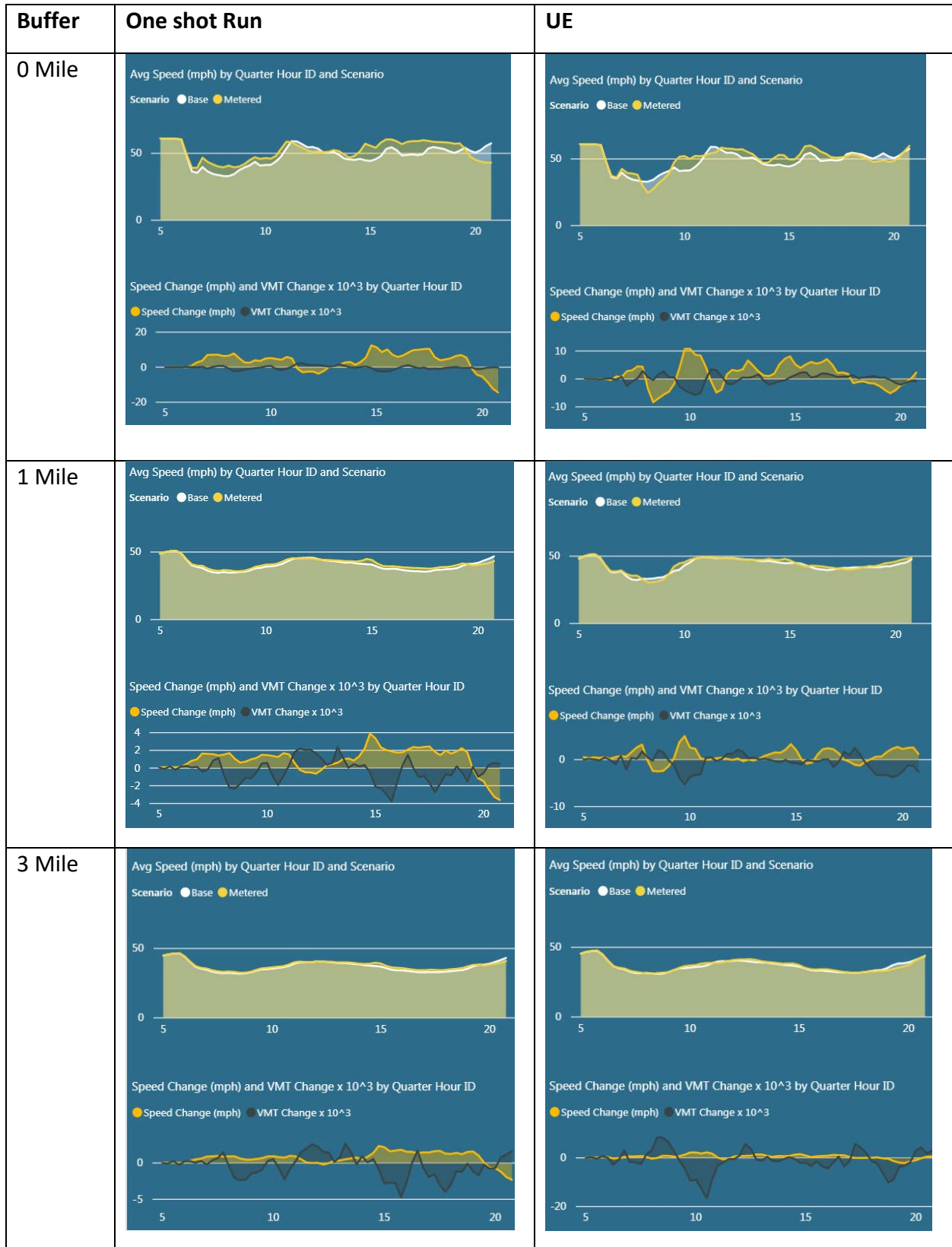
Figure C3. US 75 MOEs for Meso Corridor.

Buffer	One shot Run	UE
0 Mile		
1 Mile		
3 Mile		
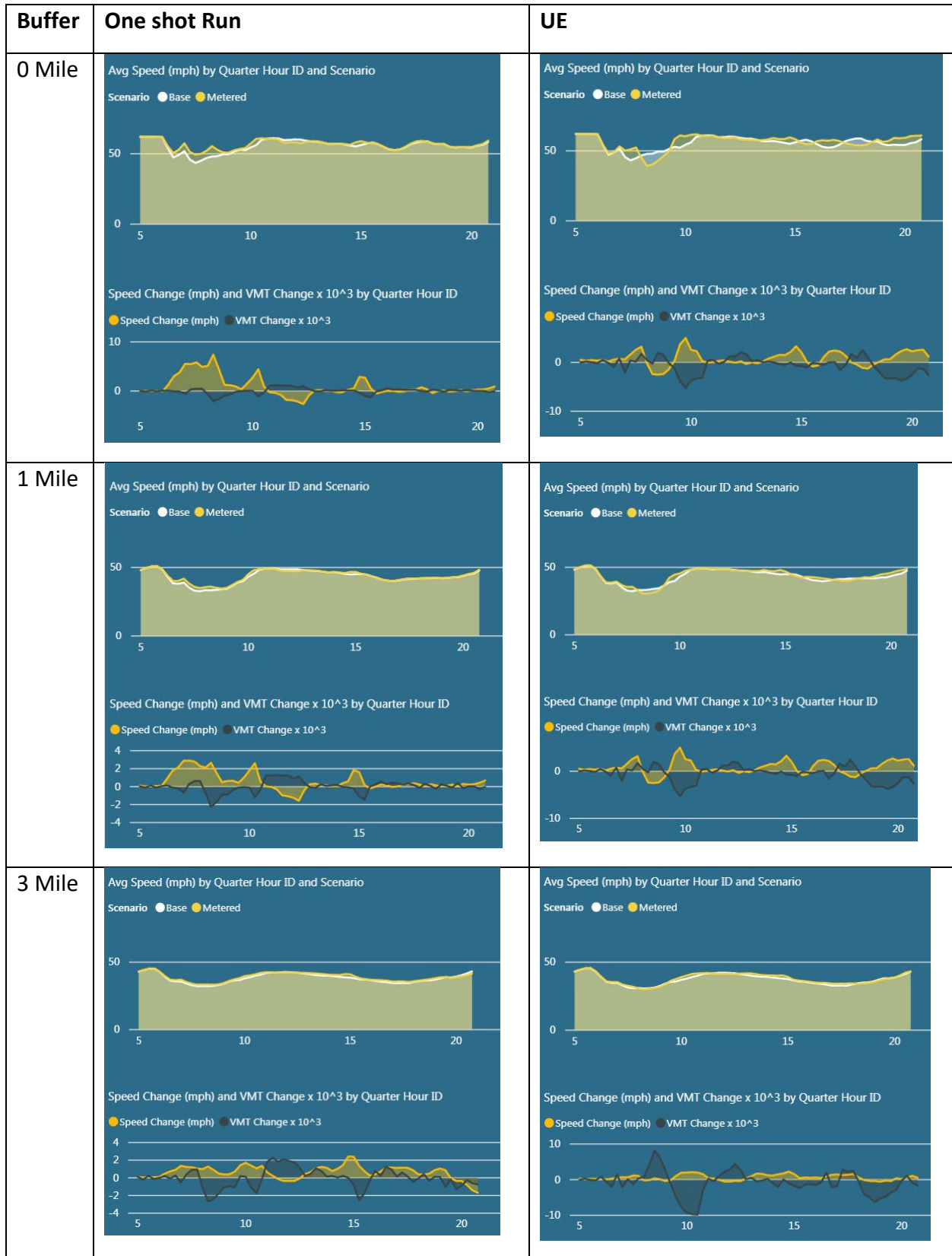
Figure C4. US 75 MOEs for Micro Corridor.

APPENDIX D: I-20 DYNUST RUN ANALYSIS

Figure D1. I-20 Micro and Meso Model Limit Illustration for 0-, 1-, and 3-Mile Buffers.

Limits	One shot Run	UE
Meso	Avg Speed (mph) by Quarter Hour ID and Scenario Scenario ⚪Base 🟡Metered Speed Change (mph) and VMT Change x 10^3 by Quarter Hour ID 🟡Speed Change (mph) ⚫VMT Change x 10^3	Avg Speed (mph) by Quarter Hour ID and Scenario Scenario ⚪Base 🟡Metered Speed Change (mph) and VMT Change x 10^3 by Quarter Hour ID 🟡Speed Change (mph) ⚫VMT Change x 10^3
Micro	Avg Speed (mph) by Quarter Hour ID and Scenario Scenario ⚪Base 🟡Metered Speed Change (mph) and VMT Change x 10^3 by Quarter Hour ID 🟡Speed Change (mph) ⚫VMT Change x 10^3	Avg Speed (mph) by Quarter Hour ID and Scenario Scenario ⚪Base 🟡Metered Speed Change (mph) and VMT Change x 10^3 by Quarter Hour ID 🟡Speed Change (mph) ⚫VMT Change x 10^3

Figure D2. MOEs for EB I-20 Freeway Only.

Limits	One shot Run	UE
Meso		
Micro		
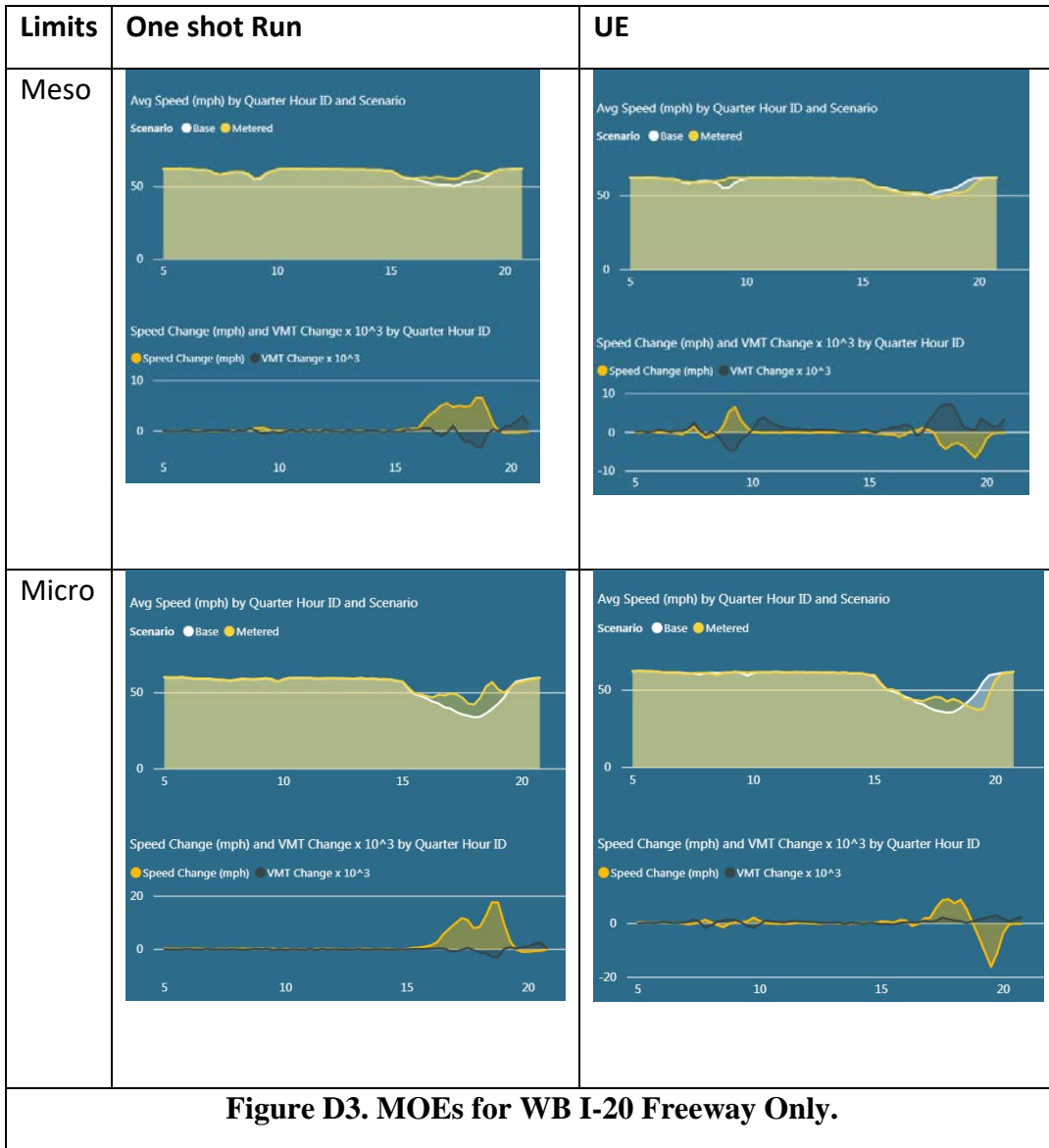
Figure D3. MOEs for WB I-20 Freeway Only.

Buffer	One shot Run	UE
1 Mile	Avg Speed (mph) by Quarter Hour ID and Scenario Scenario ○Base ●Metered Speed Change (mph) and VMT Change x 10^3 by Quarter Hour ID ●Speed Change (mph) ●VMT Change x 10^3	Avg Speed (mph) by Quarter Hour ID and Scenario Scenario ○Base ●Metered Speed Change (mph) and VMT Change x 10^3 by Quarter Hour ID ●Speed Change (mph) ●VMT Change x 10^3
3 Mile	Avg Speed (mph) by Quarter Hour ID and Scenario Scenario ○Base ●Metered Speed Change (mph) and VMT Change x 10^3 by Quarter Hour ID ●Speed Change (mph) ●VMT Change x 10^3	Avg Speed (mph) by Quarter Hour ID and Scenario Scenario ○Base ●Metered Speed Change (mph) and VMT Change x 10^3 by Quarter Hour ID ●Speed Change (mph) ●VMT Change x 10^3

Figure D4. EB I-20 MOEs for Meso Limits and Buffer Size of 1- and 3-Miles.

Buffer	One shot Run	UE
1 Mile		
3 Mile		

Figure D5. WB I-20 MOEs for Meso Limits and Buffer Size of 1- and 3-Miles.

APPENDIX E: BENEFIT COST ANALYSIS

INTRODUCTION

The objective of this project was to investigate if ramp metering can be deployed in the Dallas-Fort Worth (DFW) Metroplex to alleviate freeway traffic congestion and improve air quality. To achieve this objective, the research team identified two corridors along US 75 and I-20 and used computer simulations to evaluate the impacts of ramp metering on traffic operations and air quality in these corridors. Based on this analysis, researchers recommend that TxDOT consider implementing ramp metering at 10 on-ramps along a southbound segment of US 75. This memorandum provides value of research (VOR) calculations related to this recommendation.

BENEFITS OF RAMP METERING

Table E1 provides monetary benefits of ramp metering along US 75. These figures (for freeway only and freeway plus adjacent roadway within 1- to 4-mile radii) are reproduced from Row 5 (labeled US 75 Micro) of Tables 17 through 21.

Table E1. Calculated Benefits of Ramp Metering along US 75 Corridor.

Corridor Limits	Delay	Gasoline	Diesel	NOx	Total
Freeway Only	−$21,261.72	−$2,007.50	−$379.50	−$156.00	−$23,804.72
Freeway+1 mile	−$75,015.65	−$6,912.50	−$1,743.50	−$643.00	−$84,314.65
Freeway+2 mile	−$150,394.05	−$12,097.50	−$2,714.25	−$1,010.00	−$166,215.80
Freeway+3 mile	−$190,805.94	−$15,475.00	−$3,390.75	−$1,270.00	−$210,941.69
Freeway+4 mile	−$203,277.98	−$7,107.50	−$3,610.75	−$136.30	−$214,132.53

The numbers in this table shows daily savings during the morning period on a weekday when ramp metering is active. Yearly benefits can be obtained by multiplying each figure in the last column by 5 (days/week) and 52 (weeks/year).

Table E1 shows that the estimated benefits for this corridor increase with increased influence zone size. To be conservative in calculations, researchers used the smallest of these numbers (daily savings of $23,804.72 for freeway traffic) resulting in an estimated yearly benefit of $6,189,227.

ESTIMATED COSTS OF RAMP METERING

Table E2 provides per meter costs associated with installation and maintenance for different states. These figures are based on state of practice review conducted for this project. For the recommended DFW corridor, researchers selected a value of $150,000 for installing one ramp meter. This value is on the higher end of values reported. Based on this figure, the estimated cost of installing 10 proposed ramp meters along southbound US 75 is $1,500,000,

Table E2. Per Meter Capital and O&M Costs.

State	Capital Cost	O&M	Notes
California*	$125k–$155k (2018)	$6k (2018)	
Colorado*	$9k–$11k (2018)		Cost of equipment only. O&M lumped with general maintenance cost.
Colorado	$147k (2017)		Based on actual cost of 3 meters. https://www.codot.gov/projects/archived-project-sites/north-i-25-ramp-metering
Kansas (Pilot)*	$125K (2010)	$15k (2018)	Add $10K for radar sensor. Vehicles crashes with poles is an issue. Except routine maintenance every 6 months, labor is outsourced.
Louisiana	$86K (2010)		Project completed in 2012.
Minnesota*	$10–$15 (2018)	$2.5k (2018)	Cost of equipment only. Bulk of maintenance cost for repairing knocked poles. O&M costs have reduced after changing to LED based signals.
Washington	$130K (2018)	20 man-hr./year 3 man-hr./day (2018)	Estimates for yearly maintenance and operations.
Houston		$3.2k (2016)	Bulk of this figure is the average cost of replacing knocked down signals/poles.
Estimate for DFW	$140k	$4k + $84k	Cost of repairs plus yearly cost of one dedicated signal technician at $40/hr. (base + benefits) rounded up.
* Information provided by DOT staff.			

Except Kansas and Washington, reported operations and maintenance (O&M) cost range from $3,200 to $6,000 per ramp per year. For Kansas, the figure for $15,000 is much higher, probably because of outsourced non-routine maintenance. Washington provided O&M figures in terms of man-hours, the more significant portion of which is for proactive operations. For this project researchers used the following two components for deriving total O&M cost:

- Yearly per-ramp cost of $4,000 for repairing damage to infrastructure due to vehicle crashes. This number is obtained by rounding up the value shown in Table E2 for Houston.
- The cost of hiring a dedicated signal technician for supporting other O&M needs. For this estimate, a rate of $40/hour (base salary + fringe benefits) is assumed based on input from TxDOT staff. This results in a figure of $84,000/year ($40/hour × 2088 hours/year, rounded up).

VALUE OF RESEARCH COMPUTATIONS

Researchers used the TxDOT VOR Spreadsheet with the following assumptions:
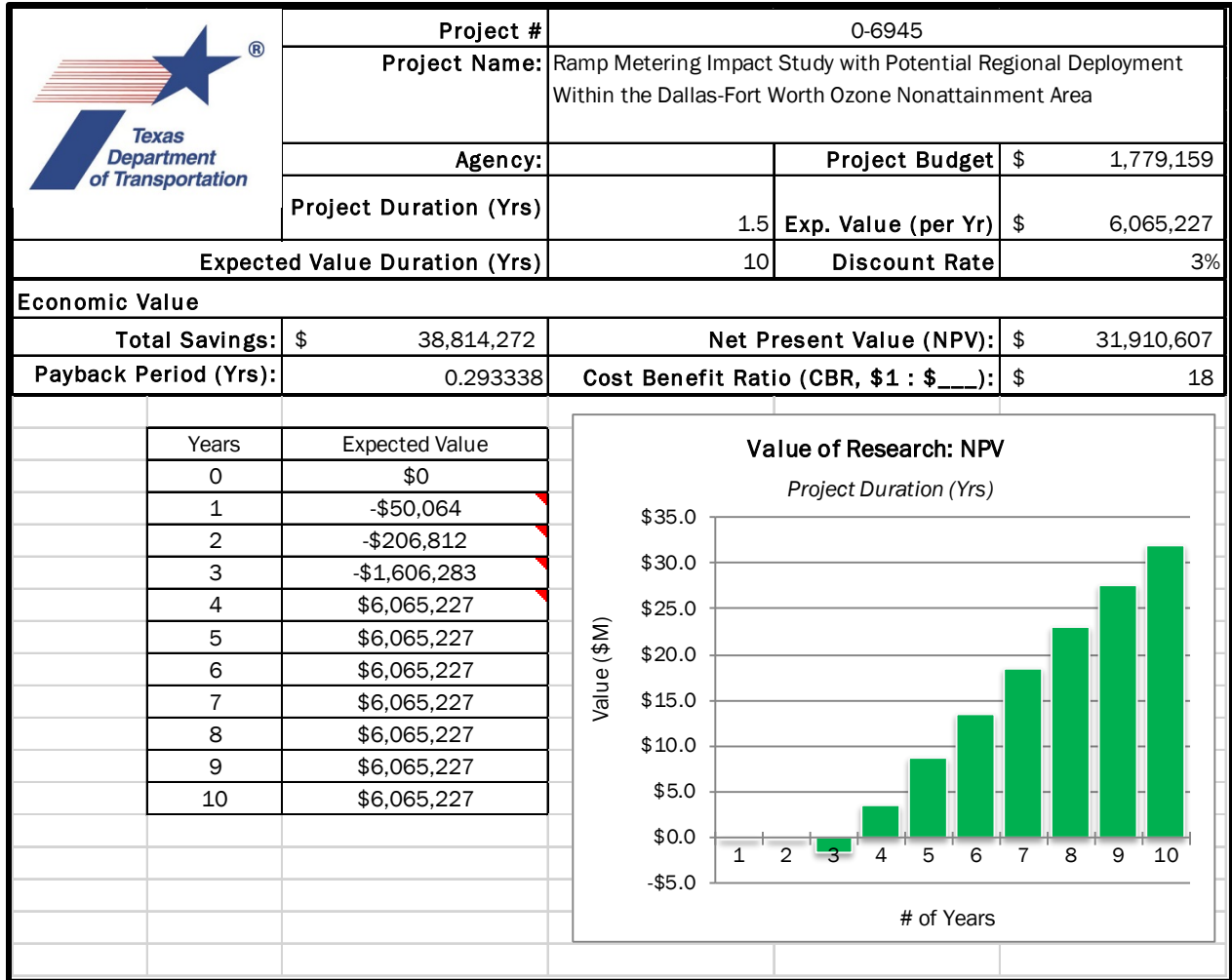
- Discount rate of 3%.
- Cost not adjusted for inflation.
- Total project cost includes cost of this research project plus costs estimated for recommended implementation.
- Years aligned with fiscal year (FY).
- A 10-year duration for calculations, beginning from the start of Research Project 0-6945 (FY 2017).
- Ramp meters installed during Year 3 (FY 2019).
- Signal technician hired at the beginning of Year 3.
- Ramp meters begin operating in Year 4 and continue operating through Year 10. Caltrans uses a value of 25 years as the life of a ramp meter. So, the number used here (7 years) is a conservative value.

Table E3 provides details of costs and benefits used in the calculations.

Table E3. Cost and Benefits over the Planning Horizon of 10 Years.

Year	Research Cost (Dollars)	Capital Cost (Dollars)	Yearly O&M (Dollars)	Yearly Benefits (Dollars)
1	(50,064)			
2	(206,812)			
3	(22,283)	($1,5000,000)	($84,000)	
4–10			(84,000 + 40,000)	6,198,227
Note: Figures in parentheses indicate costs				

As shown in Figure E1 (screen capture from the VOR Spreadsheet), the estimated net present value and benefit to cost ratio of this project are $31,910,607 and 18:1, respectively.

Project #		0-6945	
Project Name:	Ramp Metering Impact Study with Potential Regional Deployment Within the Dallas-Fort Worth Ozone Nonattainment Area		
Agency:		**Project Budget**	$ 1,779,159
Project Duration (Yrs)	1.5	**Exp. Value (per Yr)**	$ 6,065,227
Expected Value Duration (Yrs)	10	**Discount Rate**	3%

Economic Value

Total Savings:	$ 38,814,272	**Net Present Value (NPV):**	$ 31,910,607
Payback Period (Yrs):	0.293338	**Cost Benefit Ratio (CBR, $1 : $___):**	$ 18

Years	Expected Value
0	$0
1	-$50,064
2	-$206,812
3	-$1,606,283
4	$6,065,227
5	$6,065,227
6	$6,065,227
7	$6,065,227
8	$6,065,227
9	$6,065,227
10	$6,065,227

Value of Research: NPV

Figure E1. Net Present Value Computed for the 10-Year Period.