# Understanding the impacts of freeway lane closures through data: a combined analysis of NPMRDS and fixed-sensor data

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Word count: 5,345 words text + 2 tables/figures x 250 words (each) = 5,845 words

Submission Date: November 15, 2018

## ABSTRACT

While a range of analytical and modeling methodologies exist to estimate the impacts of lane closures, the direct quantification of such impacts using data is not extensively discussed. Recently, more affordable sensor technology and availability of probe vehicle data have made traffic volume and speed data readily accessible. This paper explores the use of probe-based speed data to understand the evolution and length of queues caused by freeway lane closures. The proposed methodology addresses some limitations related to the length of the segments for which speeds are provided, and is validated with spot-speed data from work zone trailers on the I-35 corridor in Austin, Texas.

Traffic volumes are also critical in quantifying the cost of lane closures. However, volumes are often available only at limited locations or for specific time periods. This work presents an approach to developing a speed/flow relationship using NPMRDS and limited fixed-sensor data. The relationship may be used later to estimate traffic volumes by time of day at other locations based only on NPMRDS speeds. Numerical analyses using traffic counts on I-35 suggest that the proposed technique is accurate and that it improves upon similar methodologies that use NPMRDS data.

The methodologies presented in this paper leverage data for a precise quantification of the impact of past lane closures, which can enable more accurate cost-benefit analyses and facilitate communications with stakeholders. It also provides better reference data to validate/calibrate prediction models and offers a more accurate estimation of queue positions to support work zone management decisions.

*Keywords*: queue length estimation, NPMRDS, lane closure, volume estimation, work zone

## INTRODUCTION

USDOT statistics show that work zones resulted in nearly 24 percent of non-recurring freeway and 10 percent of overall congestion in 2014, which is around delay time 888 million hours (*1*). Thus, transportation agencies are interested in evaluating the impacts of past lane closures for a number of applications, including the cost-benefit analysis of ITS technologies, communicating with stakeholders and the general public, and supporting the planning of future lane closures so as to limit congestion impacts. Further, the ability to quantify specific aspects of lane closure impacts, such as the length of the resulting queues, is critical to develop and validate models that can be used to predict system performance efficiently in order to support operational decision making.

While methodologies exist to estimate the impacts of closures through a range of modeling approaches (*2–20*), there is still limited understanding on how traffic volume and speeds data may be used to directly quantify such impacts (*9, 13, 21–23*).

In recent years, affordable sensor technology and probe vehicle data have become increasingly available, making traffic volume and speed data readily accessible. Data is available from traffic sensors placed at fixed locations on transportation corridors, or in portable trailers, often referred to as work-zone trailers, which may be moved over time. Complementing sensor data, GPS-equipped vehicles and drivers' cellular phones can act as probes, generating position and speed data that is collected and aggregated by multiple vendors. FHWA's National Performance Management Research Data Set (NPMRDS) makes probe-based travel time data available to all state departments of transportation and metropolitan planning organizations (*25-28)*, allowing these to establish performance targets and report on progress.

Queue formation is an expected phenomenon when lane closures are planned, and the length and position over time plays a role in operational decisions. While measuring queue lengths typically requires video data, field observations, or dedicated technology, speed data may be used to approximate it. The latter is often accomplished by identifying a speed threshold below which vehicles are considered part of a queue. The threshold is then used to assess whether a queue is present at a particular location where speeds are known. The former is straightforward to implement when point-speed data collected by radar or similar sensors is available. However, probe-based speed data is often provided as an average value for a stretch of roadway, or segment. NPMRDS segment length is variable, but they may be more than half a mile long. In this context, the average speed on the segment may not be a good indicator of whether a queue is present, since traffic may be congested at one end of the link and free-flowing at the other. This work proposes a simple methodology to address such issue by considering speeds on consecutive segments. We propose a qualitative validation approach that leverages spot-speeds from work zone trailers to evaluate our queue estimation methodology.

The methodologies and use case scenarios contained herein were developed using datasets for the I-35 corridor in Austin, Texas. Because the Texas Department of Transportation (TxDOT) has ongoing construction along this heavily traveled corridor, a better understanding of work zone queueing impacts and associated vehicle delay costs was the motivation for this work effort.

## BACKGROUND

Transportation agencies use a range of methodologies to estimate the impact of planned lane closures on freeways. Many of these approaches seek to quantify user delay costs, which requires both an estimation of travel delay and of the number of affected users. Traffic volumes are generally assumed to be collected from the field, while delay is often computed taking into account the relationship between traffic volumes and the freeway capacity when the closure is in place. The increasing availability of data provides an alternative approach to directly evaluate the impacts of past work zone closures, which may also support the validation of modeling-based solutions. The following sections briefly discuss existing tools for user delay cost estimation/prediction, and the use of data for direct estimation of work zone impacts

## Analytical Work Zone Impact Estimation Tools

Currently, the two major methods for estimating user delays associated with planned lane closures include deterministic queue models (*3, 5, 8, 20*) and microscopic simulation (*6, 10, 13, 20*). For the application of deterministic queue models, many agencies have developed Microsoft Excel-based tools to analyze work zone impacts. These tools range in complexity and require varying data inputs. FHWA developed QuickZone (*7, 12-13, 15, 26*), which is widely used among state DOTs and is based on the Highway Capacity Manual recommendations (*24*). This tool can help agencies consider impacts of alternative work zone design and mitigation strategies. Some DOTs have customized QuickZone, like Maryland's MD-QuickZone (*12, 15*). Additional spreadsheet-based tools include those developed by the New Jersey DOT (*14*), Ohio DOT (*11*), and Missouri DOT (*19*).

Queue and User Cost Evaluation of Work Zones, or QUEWZ (*4, 13, 16, 20*), is an MS-DOS based computer program that falls within the deterministic queue model category. One of the most popular analysis tools, it analyzes traffic conditions on a freeway segment with and without a lane closure in place and provides estimates of the additional road user costs and of the queuing resulting from a work zone lane closure. Road user costs calculated include travel time, vehicle operating costs, and excess emissions.

Microscopic simulation models require traffic and roadway geometric data specific to the roadway segment being analyzed. While they provide more accurate results, they also require significantly more investment in data and analysis time. Two microsimulation tools commonly used for delay queue estimation (and associated user delay calculations) include FRESIM, a freeway module from TSIS/CORSIM (*6, 13, 15*), and VISSIM (*6*).

Estimates from these methodologies are valuable for planning purposes; microsimulation can support operational decision making. All the techniques discussed in this section require traffic volume data as inputs, which is not always available for desired locations and time periods. Additionally, queue length data may be used to validate the outcomes of these techniques and calibrate relevant parameters.

## Data-Centric Approaches to Work Zone Impact Evaluation

Researchers have proposed an approach to estimate user delays costs by integrating average annual daily traffic (AADT) data, and NPMRDS data (*27, 28*). AADT is used to estimate traffic volume when the segment speed is larger than 50 mph. If the segment speed is less than 50 mph, the researchers estimated the limited volume based on speeds. The traffic volume is used to estimate vehicle miles traveled (VMT), and VMT is used to estimate travel delays. Delays on a particular day result from comparing prevalent speeds at the desired aggregation to historical values, the speed limit, or an arbitrary value. While the process includes volume adjustments when speeds are low, to avoid underestimation, AADT or limited volume estimation are likely to be too aggregate to produce precise estimates.

While previous research has used traffic cameras to validate queue length and duration during work zones (*9, 13*), there are no published examples of systematic methodologies to consistently estimate queue lengths and positions from continuously collected data, to the extent of the authors' knowledge

# ESTIMATING TRAFFIC VOLUMES BASED ON NMPRDS DATA

Traffic volumes are a critical component of user delay cost estimations and a fundamental input to the methodologies used to assess work zone impacts. However, traffic volume information is not yet widely available on a continuous basis, and practitioners often prioritize historical aggregate data, which may not adequately reflect traffic conditions at specific dates/times of day. On the other hand, probe-based speed data is becoming widely available, and traffic flow theory provides a clear relationship between speed, flows, and density. The goal of this section is to explore the potential of using limited traffic count data to develop a speed/flow relationship that can be applied to the estimation of traffic volumes based on speed data alone.

The following sections describe the data considered in our analysis, the proposed methodology, and numerical experiments used to validate the approach.

## Data

There are two major data sources used in this study: NPMRDS (*25–26*) and data obtained from portable trailers placed in the field. NPMRDS data, provided by the FHWA Office of Operations, reports observed average travel times and speeds collected from probe vehicles (both trucks and passenger vehicles), and reported at five-minute intervals. Data is provided for roadway segments (called TMCs) of variable length. When no probe vehicle travels across the segment during the specified time period, an observed travel time is not reported. For the case study described in the following sections, NPMRDS covered 80 percent of the analyzed corridor.

TxDOT places portable data collection trailers near work zones to collect speed and traffic volume data (by lane). When placed at several locations along a work zone area, these trailers can collect valuable information to evaluate the impacts from the work zone activities on traffic conditions and travel demand. In Austin, TxDOT has 14 portable trailers that can be placed at designated collection points on I-35. Each trailer collects spot speed, volume, and occupancy data for the direction of travel, in one minute intervals.

## Methodology

The proposed methodology is based on developing a typical speed-flow diagram for a specific corridor by combining speed data from the NPMRDS and traffic counts from work zone trailers. Such diagram may be later used to estimate traffic volumes based on speed data alone. While work zone trailers provide both speed and traffic volume data, this study uses speed data from the NPMRDS rather than from the work zone trailer in the development of the speed-flow relationship, given that the goal is to estimate traffic volumes at locations where a work zone trailer is not present. NPMRDS data reflects average speed over a length of freeway, thus the resulting speed-flow diagram is not entirely consistent with traffic flow theory. Numerical experiments presented below suggests that the resulting performance is adequate for the proposed application.

Our methodology consists of the following four steps: 1) aggregating traffic volume data into five-minute intervals for select work zone trailers; 2) downloading speed data from corresponding TMCs for the same time interval; 3) averaging data for each trailer; and, 4) averaging data across all trailers. The process is illustrated in Figure 2. For a selected TMC, 5 minute NPMRDS speeds (rounded to 1 mph) are plotted against the corresponding 5 minute traffic volumes, normalized by the number of lanes between 9/1/2017 and 12/31/2017 (Figure 1.1 presents only two days). Daily flow data is then averaged for each speed value (Figure 1.2). The final steps computes the average flow per lane across all work zone trailers for all considered speeds, resulting in the corridor's speed-flow curve (Figure 1.3). As an example, the use of the diagramin Figure 1.3 suggests that at 8mph the expected flow is 528 veh/hr/lane.

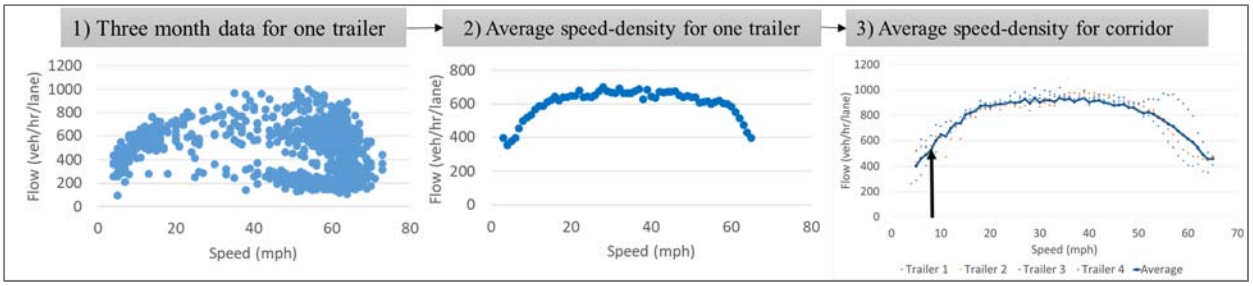

**FIGURE 1 Development of speed-flow diagram**

**Case Study**

The case study used seven of the 14 available work zone trailers, 4 for the development of the speed-flow diagram, and 3 for validation. Figure 2.1 shows the locations of trailers and TMC segments on I-35 through Austin; Figure 2.2 presents the selected trailers and TMC segments for this case study. The data was validated by comparing measured traffic volumes at the validation trailer locations to the estimates obtained from the speed-flow diagram developed for the estimation trailers as described in the preceding section.

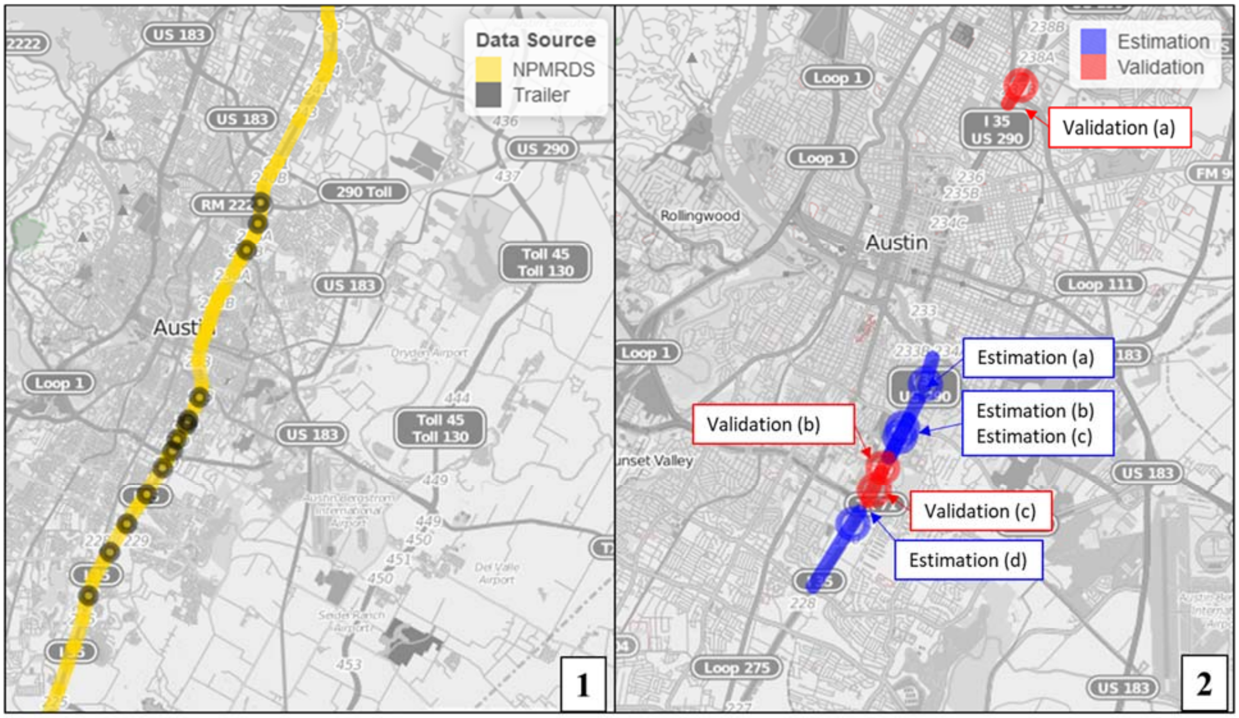

**FIGURE 2 Locations of trailers and TMC segments**

Figure 3 presents estimated traffic counts every 5 minutes using the speed-flow diagram, and the corresponding speed and volume data from the work zone trailers at 11/16/2017. The plots suggest that estimations are fairly accurate between 6 am and 10 pm. Counts are over-estimated after 10 pm (low flows) and are not as accurate at higher speeds (above 60 mph). Figure 4 presents similar results but on a day where a work zone was active near location (b) between 6 pm and 12 am. The estimated counts are similar to actual counts until 11:35 pm, when speeds start recovering. These results suggest that the proposed speed-flow diagram performs well for most non-free-flow times of the day (6 am–10 pm), and is also adequate for congested conditions such as those found during a roadway incident or in a work zone.

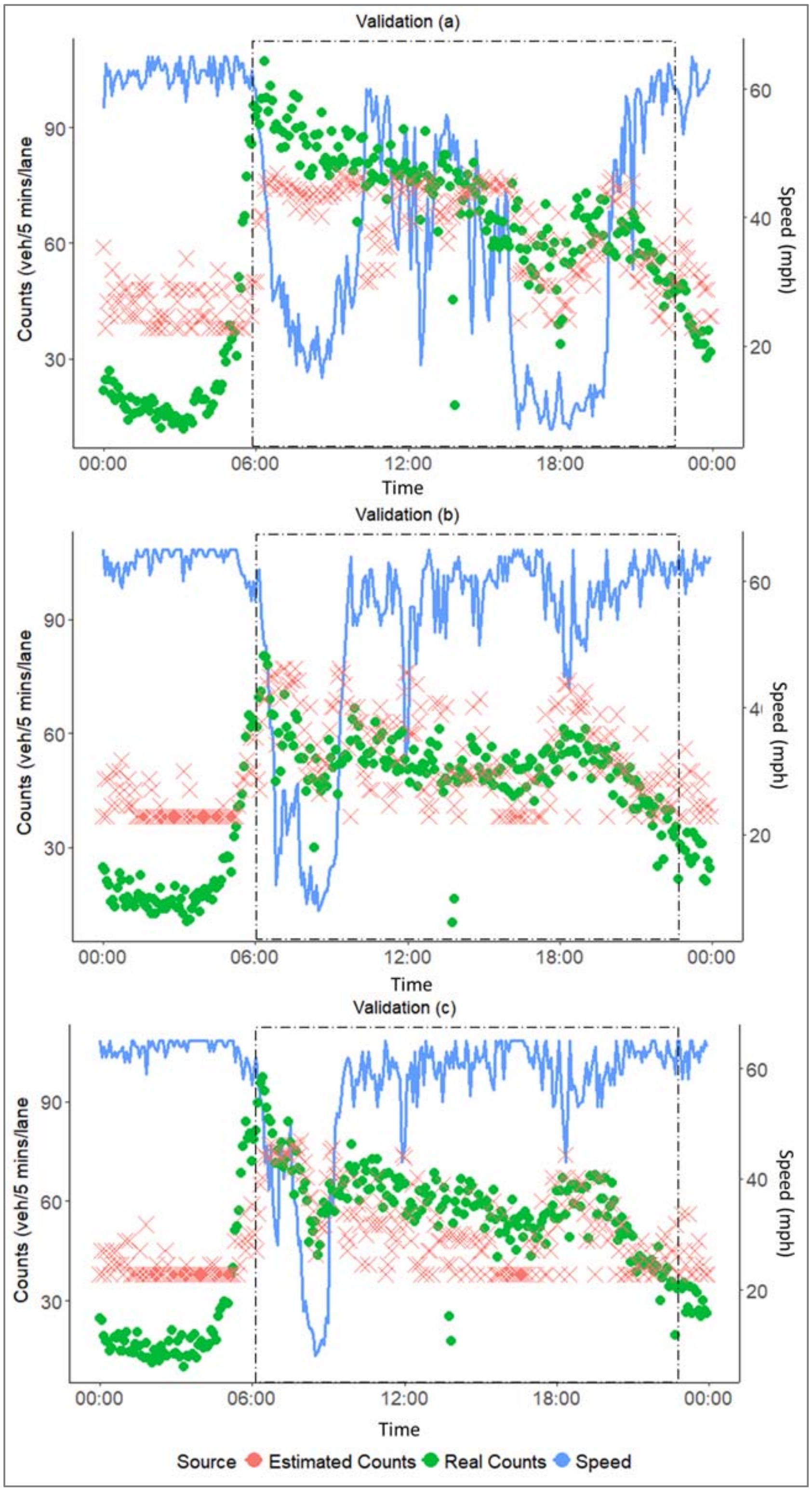

**FIGURE 3 Validation of speed-flow diagram in normal day**

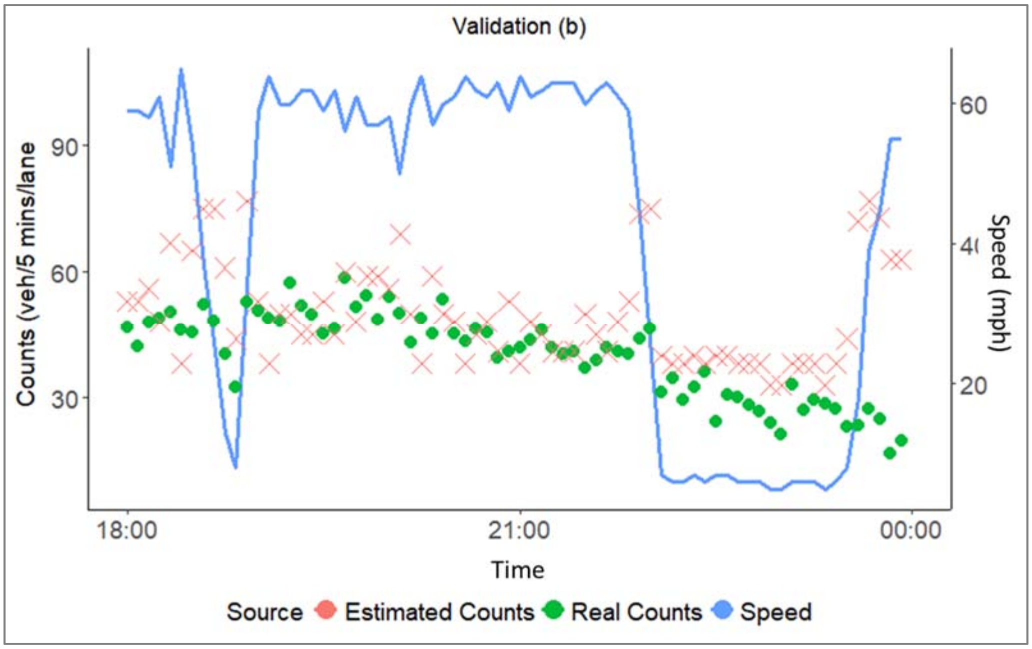

**FIGURE 4 Validation of speed-flow diagram during the work zone period**

Table 1 quantifies the performance of our volume estimation, and compares them to that of the methodology of speed limited volume presented in (*27*) and described in the Background section. Values are computed for data collected between 6 am and 10 pm from 11/1/2017 to 12/15/2017 and speed under 50 mph. The root-mean squared error (RMSE) is used to measure the average deviation between estimated and measured values. The time step at which data is aggregated when generating the speed-flow diagram is expected to have an impact on the quality of the predictions, and Table 1 presents results for several aggregations.

**TABLE 1 Comparison of RMSE between speed-flow diagram and NPRMDS**

| Interval (minutes) | Mean (vehicles) | Standard Deviation (vehicles) | RMSE: Speed-flow diagram (vehicles) | RMSE: NPMRDS (vehicles) |
|---|---|---|---|---|
| **5** | 68.62 | 17.64 | 15.22 | 89.8401 |
| **10** | 122.51 | 42.97 | 26.10 | 159.35 |
| **15** | 169.70 | 71.92 | 35.95 | 222.709 |
| **30** | 290.02 | 162.15 | 61.50 | 393.594 |
| **60** | 480.76 | 333.51 | 103.77 | 683.403 |
| **120** | 779.07 | 649.75 | 171.99 | 1,174.33 |

The results presented in Table 1 suggest that the methodology proposed in this work results in more precise volume estimations than AADT-based calculations, particularly when percent differences are considered. While performance does not change drastically when considering varying time aggregation intervals, results for 10- and 15-minute aggregations are expected to be more reliable given the lower standard deviation in the data.

## QUEUE LENGTH ESTIMATION

NPMRDS's TMC-level speed data can be used to estimate queue positions and lengths by defining a speed threshold below which a segment is considered to be part of a queue, and adding up the length of all queued segments. The use of NPMRDS data for queue length estimation is appealing given the coverage of the data, and its availability in a standard format that lends itself to the development of replicable methodologies.

TMCs may be more than one mile long, and the reported speeds represent an average across the entire segment length. The use of speeds averaged across long segment may introduce errors in the estimation of queue lengths and positions, as described in the introduction. In particular, the tail of the queue is likely to be upstream from the last segment identified as queued, while the head of the queue may be downstream from the first queued segment (Figure 5). Further, the selection of the speed threshold can clearly affect estimated queue lengths.

While the former considerations may not have a drastic impact in the estimation of user delays, they are critical when trying to identify appropriate locations for dynamic message signs (DMS) and for the design of traffic control plans, including diversions. This section proposes a simple approach for refining the estimation of queue length and position by analyzing average speeds on consecutive segments.

### Methodology

The proposed methodology estimates the length of queues upstream from a work zone based on the following assumptions: All TMCs with speeds below a pre-specified threshold (20 mph) are considered part of a queue, and the head/tail of the queue is located upstream/downstream from the last queued TMC.

The basic assumption used to estimate the position of the tail/head of the queue is that the first/last congested TMCs may be split into a congested and an uncongested region, with corresponding speeds matching those of the upstream and downstream TMCs (Figure 5). In this context, assuming that the observed TMC speed is a distance-weighted average of the speeds on the two regions (Equation 1), the positon of the queue as a fraction of the total link length is given by Equation 2. Variables are defined in Figure 5.

$$S2 = S1 * X + S3 * (1 - X),\ X \in (0,1) \tag{1}$$

$$X = \frac{S2 - S3}{S1 - S3}, X \in (0,1) \tag{2}$$

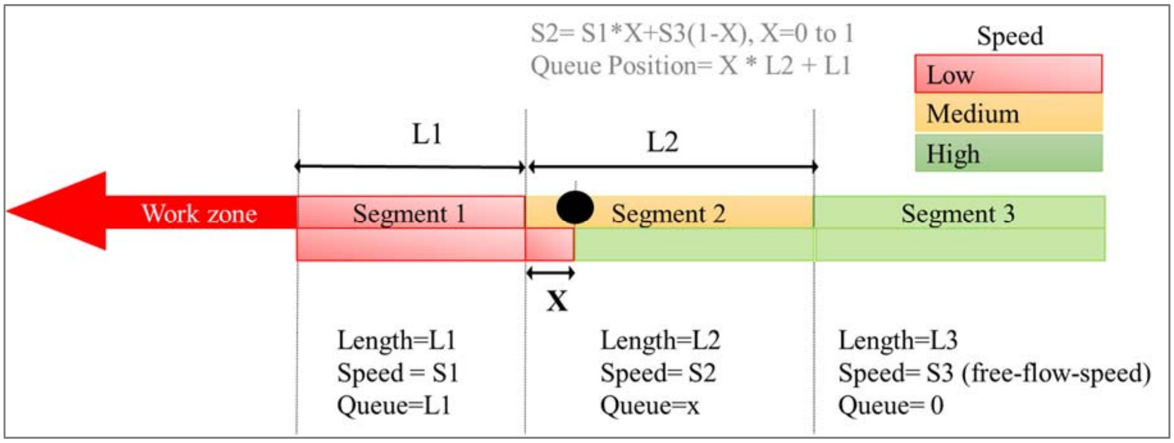

**FIGURE 5 Schematic of two speed regions within a TMC segment behind the work zone**

This methodology will not hold if the speed doesn't consistently increase/decrease in the direction of flow (e.g., if speed on segment S2 is lower than on segment S1). The latter may happen due to changes in geometric conditions, such as the presence of an auxiliary lane, that lead to uneven speeds across lanes and may bias the segment average speed. With the understanding of the exception of the former observation, we propose a methodology that is robust to small inconsistencies in speeds across TMCs. Table 2 presents the corresponding notation, and Figure 6 illustrates relevant variables.

**TABLE 2 Parameters of the queue estimation model**

| Sign | Description |
|---|---|
| $T$ | A set of TMC segments |
| $n$ | The number of TMC segments. |
| $t_i$ | A TMC segment, $t_i \in T, i \in (1, n)$ |
| $s_i$ | Segment $i$ speed |
| $l_i$ | Segment $i$ length |
| $m$ | Minimum speed |
| $t_m$ | The segment whose speed is minimum |
| $s_t$ | Queue speed threshold |
| $t_u$ | The segment whose speed is larger than $s_t$ and the most close to segment $t_m$ |
| $A_f$ | Average speed of forming queue |
| $A_d$ | Average speed of dissipating queue |
| $R_f$ | Position of forming queue as a |
| $R_d$ | Position of dissipating queue as a fraction of TMC length |
| $Q_f$ | Length of forming queue |
| $Q_d$ | Length of dissipating queue |
| $Q$ | Total queue length |

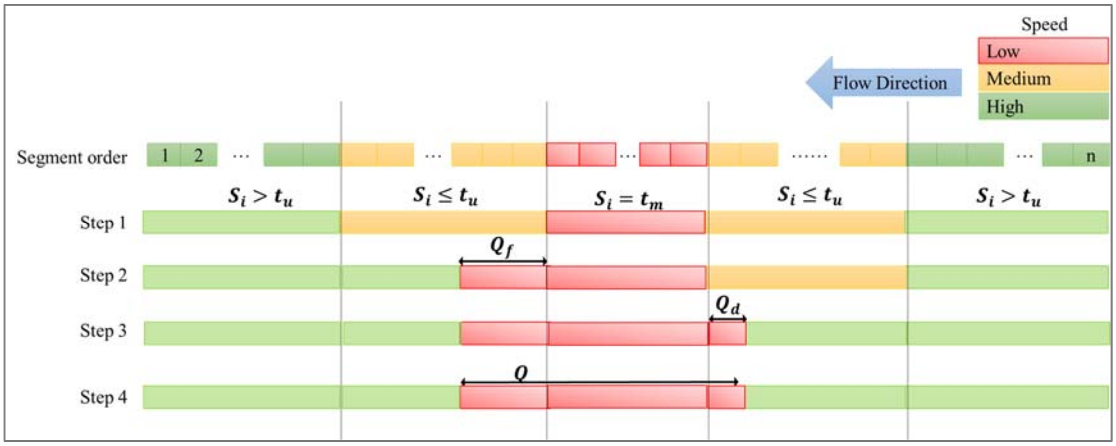

**FIGURE 6 Schematic queue length estimation**

The calculation process is as follows, for every time interval:

1. Choose a set of segments ($T$) that encompass or are close to the work zone. These segments must have potential to be impacted by the work zone.
2. Find the segment with minimum speed ($m$) among the segments in a time interval.
3. Split TMCs in two sets, downstream from m ($t_1, t_2, t_3 \ldots t_{m-1}$ ) and upstream from m ($t_{m+1}, t_{m+2}, t_{m+3} \ldots t_n$ ) (Step 1 in Figure 6).
4. Calculate the queue length downstream from $t_m$ (Step 2 in Figure 6).
    4.1.Find $t_u$
    4.2.Calculate average speed between $(t_{u-1}, t_{m-1})$, $A_u = \frac{\sum_{i=m-1}^{u-1}(s_i * l_i)}{\sum_{i=m-1}^{u}(l_i)}$
    4.3.Calculate the position of the queue head, $R_u = \frac{A_u - s_u}{s_m - s_u}$
    4.4.Calculate the forming queue length, $Q_u = \sum_{i=m-1}^{u}(l_i) * R_u$
5. Calculate the queue length upstream from $t_m$.(Step 3 in Figure 6)
    5.1.Find $t_d$
    5.2.Calculate average speed between $(t_{m+1}, t_{d-1})$, $A_d = \frac{\sum_{i=m+1}^{d-1}(s_i * l_i)}{\sum_{i=m+1}^{d-1}(l_i)}$
    5.3.Calculate the position of queue end, $R_d = \frac{A_d - s_d}{s_m - s_d}$
    5.4.Calculate the dissipating queue length, $Q_d = \sum_{i=m+1}^{d-1}(l_i) * R_d$
6. Calculate he total queue length, $\mathrm{Q} = Q_u + Q_d + \sum_m l_i$ (Step 4 in Figure 6)

There were 40 work zones on I-35 in Austin, Texas, between September 2017 and December 2017.We chose two work zones with locations close to trailer traffic collection points. Given that the estimated queue length depends on the selected threshold, this study presents queue length estimates using 30 mph, 40 mph, and 50 mph thresholds. Speed data from work zone trailers is used to validate results qualitatively, by verifying if the corresponding speeds are below the specified threshold when the queue is predicted to reach the trailer.

Figure 7 describes the location of the first analyzed work zone (Closure 1) and relevant data sources, including the location of work zone trailers and the lengths of TMCs. The work zone closure is approximately 1 mile long and it covers two on-ramps and two off-ramps. Construction took place between 10 pm and 5 am. To simplify the analysis, this study presents data between 9:30 pm and 12 am.

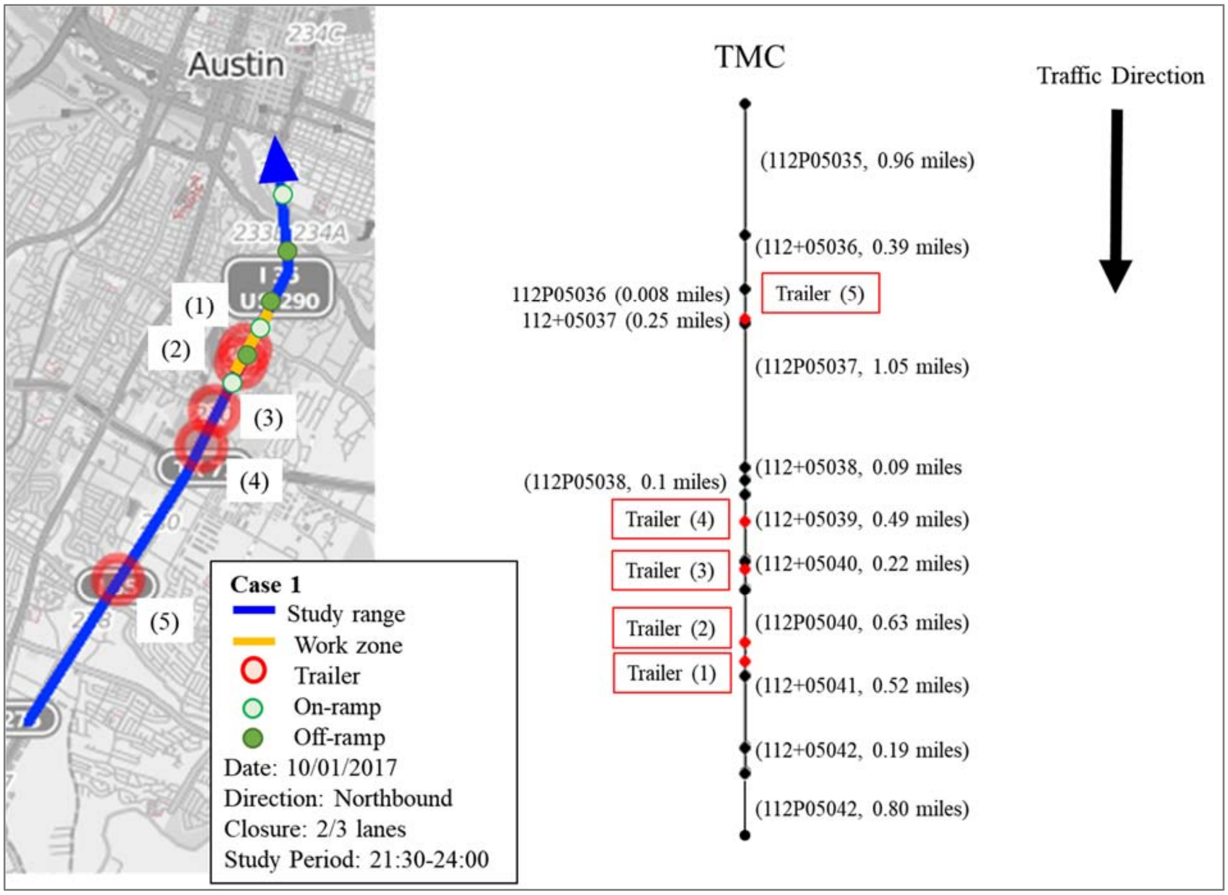

**FIGURE 7 Work zone study area for Closure 1**

Figure 8 presents the queue head and tail location along with average TMC speeds (8.1) and work zone trailer speeds (8.2) as a function of time, suggesting that a queue starts forming before 10 pm and is present till after 11:30pm. The NPMRDS-based estimates of the presence of a queue with respect to the location of trailers 3 and 5 are consistent with the corresponding speed data. Results show a discrepancy between NPMRDS and work zone trailer speeds at other trailer locations. Trailers 1 and 4 are located near an entry ramps where an auxiliary lane is present. The higher speed on such lanes is likely to be biasing the reported speed by the trailers. The higher speeds on trailer 2 when compared to NPMRDS data may reflect an error in the sensor. However, it is also possible that the sensor is placed downstream from a bottleneck, which is consistent with the fact that there is an exit and an entrance ramp on the TMC where trailers 1 and 2 are located, and Figure 8.1 suggests that the queue starts forming on such TMC.

The position of the queue tail does not vary significantly with the selection of a speed threshold, with an average difference of 0.24 miles. The position of the queue head is however unstable for speed thresholds higher than 30 mph. The length of the queue reflects the latter trend (Figure 9); while maximum queue lengths do not change significantly across thresholds (ranging between 2.9 and 3.5 miles), estimated lengths at specific points in time show large differences, with higher speed thresholds resulting in longer queue estimates.

Figure 8 also illustrates how the proposed queue estimation model may fail to identify situations where the queue "splits" due to bottlenecks caused by ramps within the analysis zone, which seems to be the case around 11:20 pm.

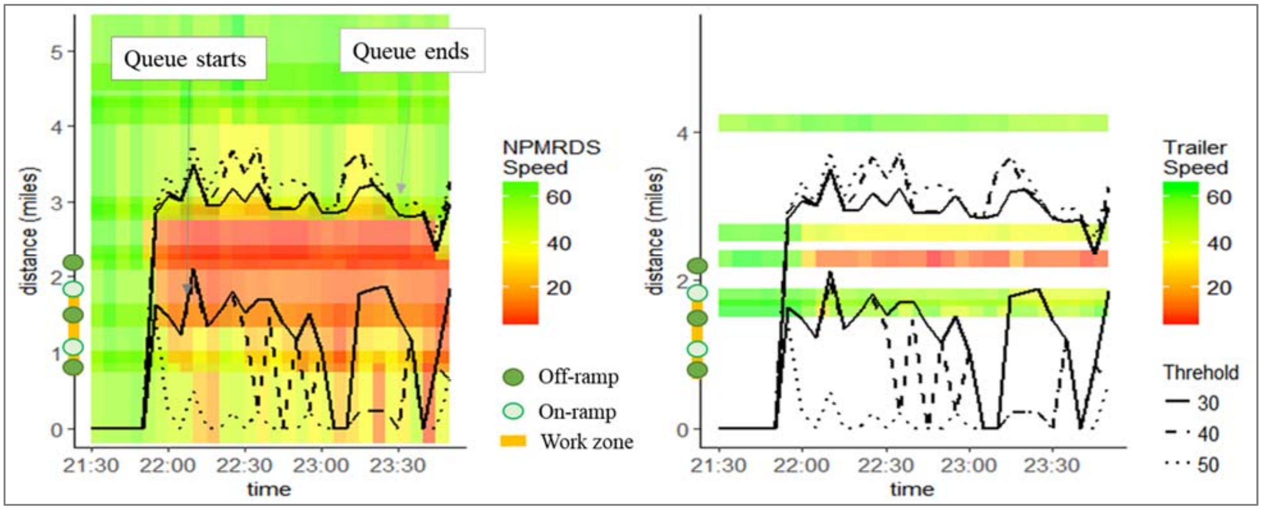

**FIGURE 8 Estimated queue position over time (Closure 1)**

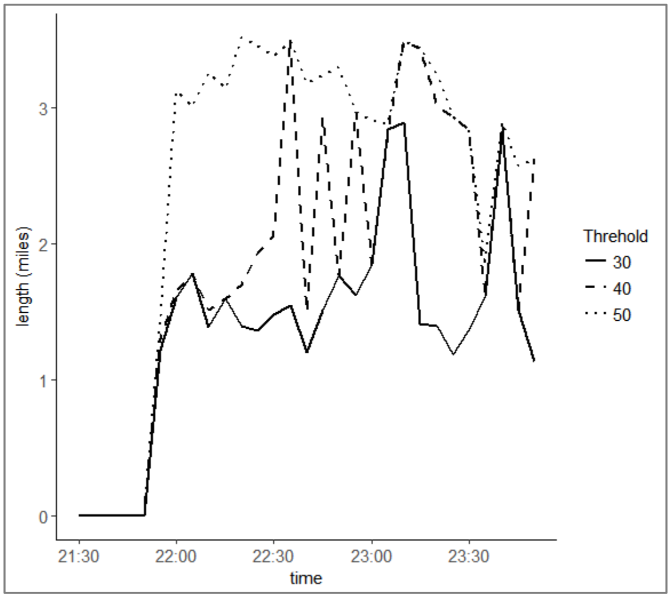

**FIGURE 9 Queue length estimation (Closure 1)**

Figure 10 describes the location of the first analyzed work zone (Closure 2) and relevant data sources, including the location of work zone trailers and the lengths of TMCs. The work zone closure is approximately 0.4 mile long, between an entering and an existing ramp. Construction took place between 10 pm and 5 am. To simplify the analysis, this study presents data between 9:30 pm and 11 pm.

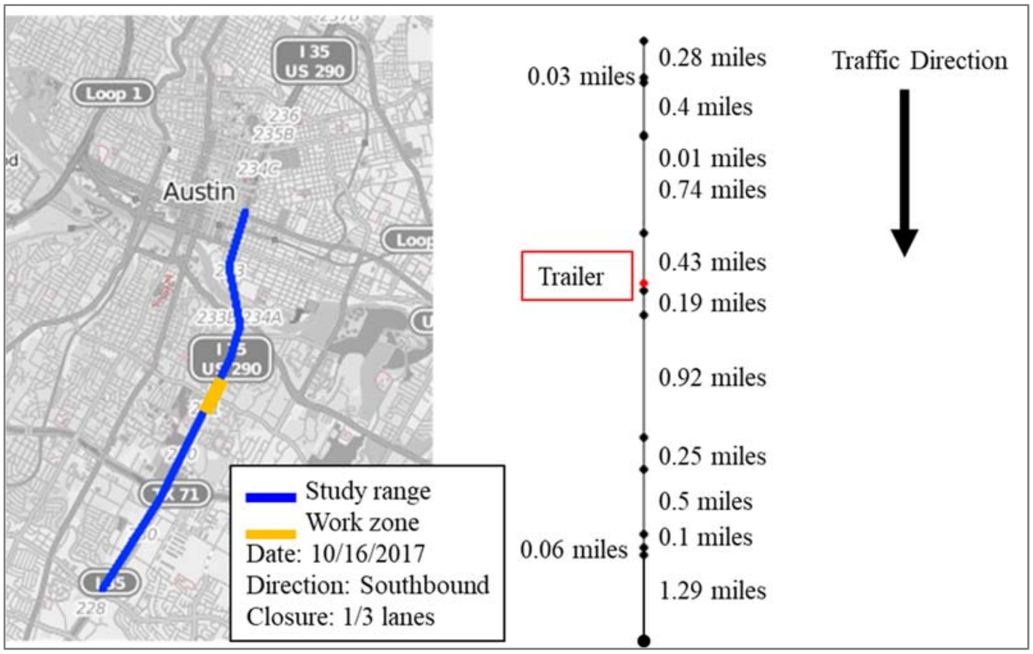

**FIGURE 10 Work zone study area for Closure 2**

Figure 11 presents the queue head and tail location along with average TMC speeds (11.1) and work zone trailer speeds (11.2) as a function of time, suggesting that a queue starts forming before 10 pm and is present till around 11:30pm. The NPMRDS-based estimates of the presence of a queue with respect to the location of trailer is consistent with the corresponding speed data.

The position of the queue tail does not vary significantly with the selection of a speed threshold, with an average difference of 0.19 miles. The position of the queue head is however presents larger difference with higher than 30 mph between 10:10 pm and 10:20 pm. The length of the queue reflects the latter trend (Figure 12); while maximum queue lengths do not change significantly across thresholds (ranging between 1.2 and 1.5 miles), estimated lengths at specific points in time show large differences, with higher speed thresholds resulting in longer queue estimates.

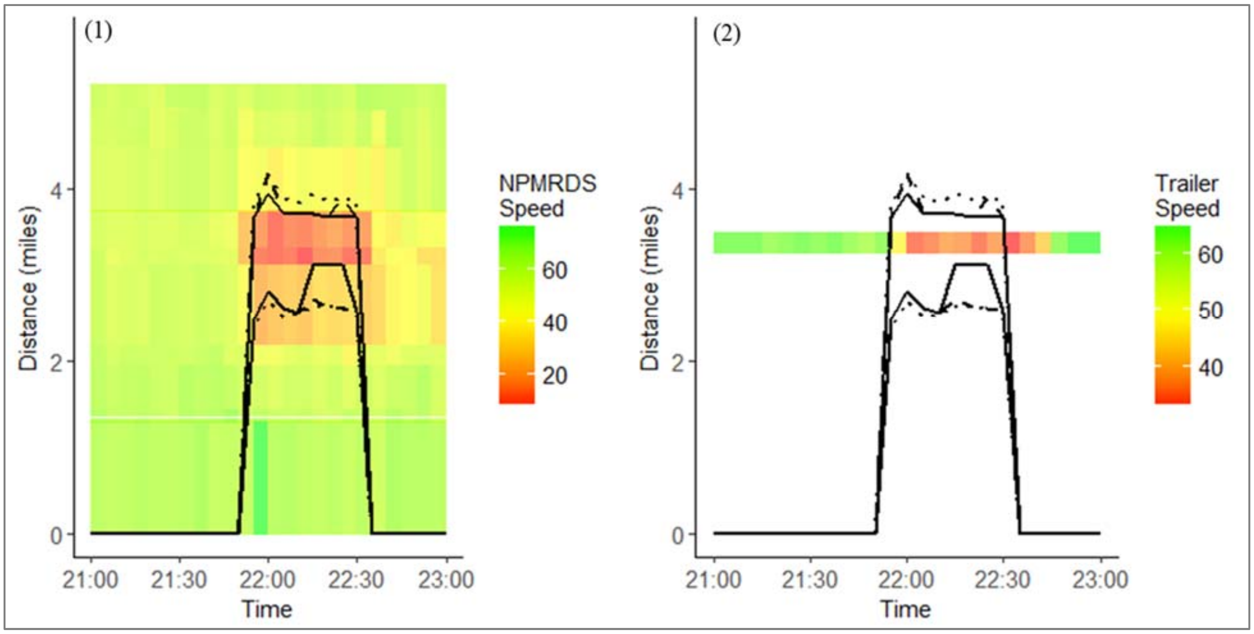

**FIGURE 11 Estimated queue position over time (Closure 2)**

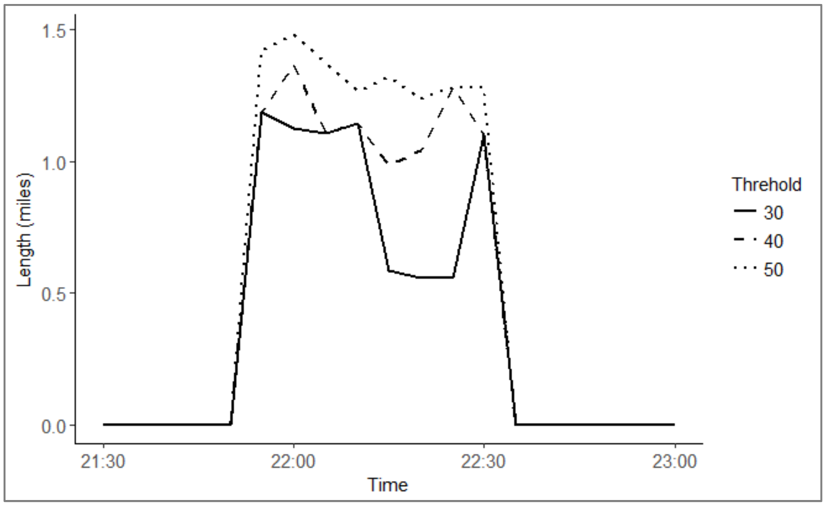

**FIGURE 12 Estimated queue position over time (Closure 2)**

## CONCLUSION

This paper presents an approach to using probe-based speed data in the analysis and quantification of work zone impacts. We propose a technique to estimate queue lengths and position over time based on NPMRDS speed data. The use of speed data to analyze queues involves defining a speed threshold below which vehicles are considered to be part of a queue. Our method takes into account that NPMRDS speeds are reported as an average value for segments of varying lengths, which may affect the precision of the queue position estimates. We used NPMRDS and sensor speed data collected on I-35 in Austin, Texas, to test our methodology and validate its results. The analysis suggests the approach provides reasonable estimates of queue evolution over time, and that speed thresholds of 30 mph or lower are likely to provide more stable results. It also illustrates some of the complexities of measuring real queue lengths in the field, which makes validation efforts more challenging.

This work also discusses a method to approximate traffic volumes based on NPMRDS speeds by estimating a corridor-level speed-flow relationship based on data from a limited number of sensors. Time-of-day counts are often not available for all freeway/highway segments on a continuous basis, so the use of NPMRDS data to estimate such values is very promising for a range of applications, including user-delay cost estimation and generating inputs for analytical models of work-zone impacts. Our approach was validated using field traffic counts from portable sensors on I-35. Average errors (RMSE) were in the order of 20 percent, and a detailed analysis of estimated and real traffic counts for both a typical day and a work zone day suggests that the model performs well within most traffic conditions (6 am–10 pm), although it tends to over-estimate traffic counts in low-volume/high-speed situations.

This effort complements existing uses of NPMRDS data by providing techniques to quantify the length of queues due to lane closures, and an approach to produce more accurate traffic volume estimates when sensor traffic counts are available for calibration. Further work will explore the use of additional data sources, such as closely spaced speed sensors and video data, to validate and improve queue length estimates. We will also study the use of machine learning techniques to identify different cross-section types for the estimation of speed-flow diagrams, which may lead to more accurate estimates.

Data sources such as NPMRDS provide a valuable opportunity to develop replicable and transferable techniques to support agencies’ planning and operation decisions. The methods discussed in this work have been implemented in a simple web application available from the authors.

## AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception, design, and direction: A. Chen, Y. Li, T. Zhou, H.Ross, N. Ruiz-Juri; analysis and interpretation of results: A. Chen, L. Yun, N. Ruiz-Juri; draft manuscript preparation: A. Chen, H.Ross, N. Ruiz-Juri. All authors reviewed the results and approved the final version of the manuscript.

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