JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
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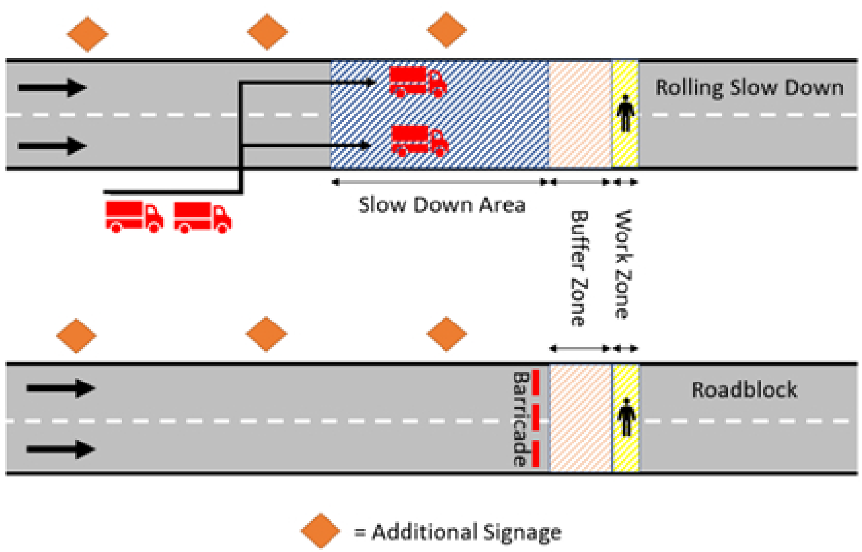
Safety and Mobility Analysis of Rolling Slowdown for Work Zones: Comparison with Full Closure



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JOINT TRANSPORTATION RESEARCH PROGRAM

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NOTICE

COVER IMAGE

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16. Abstract

There are times when the traffic lanes through a work zone must be kept clear for activities such as placing overhead beams, erecting overhead signs, and installing power lines, and other temporary roadway work activities. As an alternative to a full road closure, a rolling slowdown can typically provide up to 30 minutes to complete such activities without bringing approaching traffic to a complete halt. Using data from recent rolling slowdowns and full closures carried on the Indiana interstate network and a simulation approach, this study compares rolling slowdowns to full closures from safety and mobility standpoints. The study suggests that while rolling slowdowns are more impactful in terms of travel times, they are a safer option than full closures as they often form a forward moving shockwave causing, lower hard braking rates, and consequently a lower probability of causing a crash.

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EXECUTIVE SUMMARY

Introduction

There are times when the traffic lanes in a work zone must be kept clear for activities, such as "placing overhead beams, erecting overhead signs, . . . and installing power lines." (ARTBA 2014; INDOT, 2017). As an alternative to a full road closure, a rolling slowdown of traffic in advance of the work zone can typically provide up to 30 minutes for the completion of the previously-mentioned activities without bringing approaching traffic to a complete halt.

The selection of a temporary traffic control strategy for a work zone needs to account for both the safety and mobility of roadway users and workers. Short-duration work zone activities requiring the full closure of all roadway lanes for durations equal to or less than 30 minutes can implement either a full closure or a rolling slowdown. This study aims to determine the most appropriate temporary traffic control strategy to use under specified circumstances (time-of-day, work duration, work type, and work location).

Findings

For the safety perspective, five rolling slowdown and full closure cases were chosen for this study—all of them performed on Indiana's interstate system in 2020 and 2021. Generally, rolling slowdowns had either stationary- or forward-moving shockwaves. In contrast, full closures always had backward-moving shockwaves.

For rolling slowdowns, the average shockwave velocity was 12.68 mph and moving the same direction of travel (forward-moving shockwave). The average relative velocity was 67.2 mph, and the average hard-braking events were at a rate of 2.46 HB/1,000 veh/hr. The average shockwave velocity was -6.54 mph for the full closures and moving in the opposite direction of travel (backward-moving shockwave). The average relative velocity was 84.34 mph, and the average hard-braking events were at a rate of 9.07 HB/1,000 veh/hr. For the mobility analysis, three work zone durations were simulated at six different times of the day for full closures, while rolling slowdowns were simulated using different lead-vehicle speeds for the exact scenarios.

Except for two cases, it was observed that full closures tend to have shorter impact durations on travel times than rolling slowdowns. Additionally, for both strategies, as the work duration increased from 10 minutes to 20 minutes, the impact on travel times nearly doubled. However, when the work duration increased to 30 minutes, the impact on travel times nearly quadrupled, showing an exponential trend between the work duration and the impact on travel times.

Implementation

This research provides new insight into safety measures by introducing the relationship between relative velocities and hard braking rates. On average, higher relative velocities cause higher hard braking rates. This relationship is beneficial when analyzing temporary traffic control strategies that require all lanes of travel to either come to a halt or require vehicles in these lanes to travel at lower/higher speeds than vehicles upstream.

Rolling slowdowns often have forward-moving queues that result in low relative velocity values and consequently lower hard-braking events. However, a rolling slowdown operation may come to a temporary stop when work downstream takes longer than anticipated. In such cases, the resulting shockwave would be expected to move backward, making the rolling slowdown operation lose its safety advantage. On the other hand, full closures vehicles will always be accumulating in a backward-forming queue, which is when a queue forms in the opposite direction of travel (backward-forming shockwave). It would, hence, result in higher relative velocities and hard-braking rates, making rolling slowdowns a safer option when compared to full closures.

From the mobility perspective, the simulation environment results showed that for most cases full closure is the superior alternative for minimizing travel times compared with a rolling slowdown. This finding, in part, is due to the additional time required for a rolling slowdown operation when the lead vehicles travel at pacing speed and before work begins at the work zone site (clearance distance). This extra pacing distance must be traveled before work begins to ensure all vehicles at regulatory speed have exited the segment between the lead pacing vehicle and the worksite. In comparison, full closure will close the road adjacent to the worksite. Hence, full closures will not require the added buffer of safety to ensure the exit of regulatory speed vehicles before the commencement of work zone activities, which results in less impact on travel times. Although full closures, for most cases, cause a lower impact on total travel times, this was only by a few minutes advantage compared to rolling slowdowns. On the other hand, rolling slowdowns were safer for roadway users in terms of hard-braking rates.

It is recommended that overseeing authorities (i.e., DOTs) should require designers seeking the preferred MOT strategy to provide a comprehensive description of their designs and to have all stakeholders (i.e., DOT, police, and contractors) involved in the review process. This plan can help in detecting and anticipating potential problems.

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1. INTRODUCTION

There are times when the traffic lanes through a work zone must be kept clear for short term activities such as placing overhead beams, erecting overhead signs, installing power lines, and other temporary roadway work activities (ARTBA, 2014; INDOT, 2017). As an alternative to a full road closure, a rolling slowdown can typically provide up to 30 minutes to complete such activities without bringing approaching traffic to a complete halt. A rolling slowdown, seen in Figure 1.1, also known as a rolling roadblock, rolling block, pacing operation, or traffic pacing, is a highway traffic control technique used to temporarily slow or stop traffic upstream of construction or maintenance activities requiring a full short-term (10–30 minutes) closure of the roadway. Rolling slowdowns allow workers full access on and above a roadway while having a safe environment by completely removing traffic that would ordinarily be in close proximity to workers.

Figure 1.1 Rolling slowdown (Wanner, 2017).

1.1 Background and Temporary Work Zone Traffic Control Strategies

Temporary traffic control strategies for roadway construction and maintenance activities require careful planning and execution to ensure the safety and efficiency of both workers/crews on roadways and travelers, especially when conducted on roads with heavy traffic volumes such as the interstate network. Poor planning and the selection of a traffic control strategy could trigger a ripple effect impacting traffic for miles upstream and in some cases, cause accidents (Li & Bai, 2009; Smadi & Baker, 2008).

Based on the type of the roadway work and/or maintenance type, the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) provides guidance (in the form of detailed designs and specifications) to roadway designers for the selection and design of temporary traffic control strategies. However, it is still at the designer's discretion to choose the most appropriate traffic control strategy for each roadway work zone, on a case-by-case basis. Thereafter, the selected strategy is subject to DOT review and approval.

Roadway work activities such as setting bridge beams, placing overhead sign structures, and pulling wires or cables across the roadway could cause inherent danger to traffic if the operations are conducted while traffic is on the roadway. Hence, removing the traffic from the work area eliminates the risk, for travelers, construction workers, and inspectors, should some unexpected incident occur. Two temporary traffic control strategies can be utilized for the aforementioned unique roadway work activities: rolling slowdowns or temporary full closures, as seen in Figure 1.2. In a rolling slowdown, rolling/pacing vehicles (one per lane of traffic) would travel slowly and block vehicles behind them to provide adequate time for work downstream to

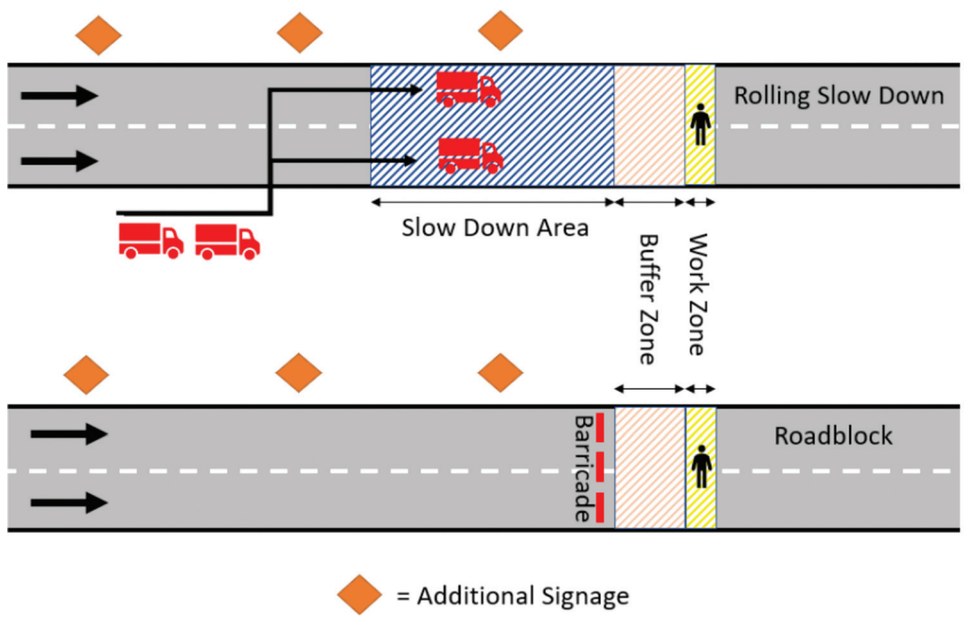


Figure 1.2 Rolling slowdown and full closure schematics (Saha & Kobryn, 2021).

be completed. If the timing and pacing speed of the operation is successful, traffic will not reach a complete halt (ATSSA, 2013). In contrast, full closures would close the road resulting in a total stoppage to traffic flow until work is completed downstream.

1.2 Problem Statement and Research Objective

The selection of a temporary traffic control strategy for a work zone needs to account for both safety and mobility of roadway users and workers. Short duration work zone activities requiring full access to all roadway lanes, for durations equal to or less than 30 minutes, can implement either a full closure or a rolling slowdown. The objective of this study is to determine the most appropriate temporary traffic control strategy to use under specified circumstances (time of day, work duration, etc.) or, conversely, to determine circumstances when a specific strategy (rolling slowdown or full closure) can be used. Hence, this study will analyze the effectiveness of rolling slowdowns and temporary full closures for work zones based on two metrics—the safety of roadway users and travel times of motorists.

1.3 Report Organization

The first chapter provides the research's background, the problem statement and research aims, and safety and mobility considerations for traffic control strategies. The results of the literature review undertaken for this study are summarized in the second chapter. The research methodology is presented in the third chapter. The fourth chapter presents the safety evaluation results through the analysis of hard-braking events and the mobility simulation results through the total time of impact on travel times. Finally, the fifth chapter contains the conclusions and recommendations of the study.

2. LITERATURE REVIEW

This chapter examined a collection of research studies on the different types and corresponding considerations of traffic control strategies (TCSs) for work zones. Mainly, TCSs have been studied from the safety and mobility perspectives for road users and workers.

2.1 Impact of Work Zone Traffic Control Strategies

This section highlights studies on the safety impacts of work zone TSCs using crash data, trajectory studies, and emerging approaches such as crowdsourced data (connected vehicles data). In addition, microsimulation traffic mobility studies are listed, and conclusions from these studies are stated.

2.1.1 Safety of Road Users

The National Work Zone Crash Information Clearinghouse (NWZSIC, http://www.workzonesafety.org) serves as the comprehensive resource on roadway construction zone with a primary focus on work zone safety. Based on NWZSIC, between 2018 and 2019, fatal crashes in work zones increased by 11%, while fatal crashes outside of work zones decreased by 2%. The 11% increase in work zone fatalities outpaced the 0.3% increase in overall highway construction spending. In 2018, 754 people, including 124 worked zone workers, died in work zone crashes.

2.1.1.1 Crash data. Prior studies have evaluated work zone safety by analyzing crash data. Such studies investigated the impact of contributing factors (vehicle class, time of day, DUI, and roadway class, and speed limit) on the number of accidents (Al-Bdairi, 2020; Theofilatos et al., 2017; Yang et al., 2013) and the crash severities (Mokhtarimousavi et al., 2019; Osman et al., 2018) near work zone areas. Although these studies provided general insights on the effects of a variety of highway work zone features that influence traffic safety, accidents are rare events and (1) only include discrete measures of explanatory variables and outcomes, and (2) fail to capture the continuous effects and magnitude of work zone activities on traffic safety.

2.1.1.2 Trajectory data. With the emergence of large-scale data collected from on-site cameras and onboard vehicle sensors (Wejo, 2020), researchers can observe and analyze the dynamics of traffic flow at an unprecedented level of granularity. Historical accident data is no longer a necessary condition for transportation agencies to conduct safety analysis. Instead, traffic conflict analysis using surrogate safety measures (SSMs) has generated new research interest in traffic safety studies. Several studies have applied SSMs as traffic conflict techniques in highway work zone analysis using vehicle trajectory data. Time to collision (TTC), stopping distance index (SDI), and deceleration rate to avoid the crash (DRAC) delineated from vehicle trajectory data were utilized to represent highway work zone crash risks (Park et al., 2018; Weng et al., 2014; Weng et al., 2018). Driver behavior analysis such as car-following behavior, lane-changing behavior, and shock-wave analysis extracted from vehicular trajectory data has been explored in interstate work zone mobility studies (Li et al., 2015; Raju et al., 2020).

2.1.1.3 Crowdsourced probe data. Trajectory data can be used from prior studies or collected on-site through cameras within a specific time range but may fail to capture real-time congestion and crashes in work zones. To monitor real-time congestion and safety in work zones, the Indiana Department of Transportation (INDOT) developed a weekly work zone report and dashboards to analyze interstate work zones' real-time mobility and safety (Mekker et al., 2019). The dashboard is a real-time visualization tool consisting of a spatial-temporal congestion graph, a frequency of speed map, and the number of hard-braking events (defined as any vehicle decelerations greater than

8.76 ft/s^2. See Desai et al. (2021) using the crowd-sourced probe data. An emerging SSM—hard-braking events collected from the INDOT dashboards (Day et al., 2016; Desai et al., 2021; Hunter et al., 2021) have been applied in interstate and intersection safety studies. Approximately one crash/mile for every 147 hard-braking events occurs in and around interstate work zones (Desai et al., 2021).

2.1.2 Mobility

This section highlights the literature findings on mobility impacts of work zone TSCs. Mainly, accurate data comes from on-site observations; however, it is expensive to collect a comprehensive dataset for all studied scenarios. Alternatively, microsimulation approaches mirror the impact hypothetical scenarios could have on traffic.

2.1.2.1 Model calibration using field data. The United States Department of Transportation (USDOT) provides guidance, procedures, and recommendations to identify work zone impacts on mobility better and determine mitigation strategies. Most of the current practices from DOTs are based on the capacity model for short-term work zones proposed by *Highway Capacity Manual* (Transportation Research Board, 2016). The HCM capacity model for short-term work zones is a parametric function that explores a deterministic relationship between the work zone features and highway capacity. The HCM capacity model has been extensively applied in evaluating work zone traffic control strategies (TCSs) such as full closure (Batson et al., 2009; DeVries et al., 2014) and lane closure (Elefteriadou et al., 2008; Hajbabaie et al., 2017; Transportation Research Board, 2016; Ozbay & Bartin, 2008; Schroeder et al., 2015; TN.gov., n.d; Washburn et al., 2008) from the perspective of mobility. However, highway capacity near work zone areas is likely to be influenced by critical factors such as speed limit, the number of construction sites, and highway geometry—factors that the deterministic model cannot capture. A review of both deterministic and stochastic models can be found in surveys (Mashhadi et al., 2021; Weng & Meng, 2013).

Stochastic models such as regression models and commonly used machine learning models have explored the relationship between contributing factors and highway work zone capacity. Regression models are able to interpret work zone capacity on the basis of speed-flow and speed-density relationships. Additionally, in prior studies, an increase in the number of construction sites per work zone, a change in the geometric alignment, and a lower speed limit near work zone were shown to result in a lower work zone capacity (Lu et al., 2018; Weng & Yan, 2014). Machine learning approaches take advantage of large-scale datasets (probe data, multi-contextual data, and work zone reports) to predict the work zone capacity, operational speed, and queue length near work zone (Bae et al., 2017; Du et al., 2017; Kamyab et al., 2020; Weng & Meng, 2012). The prediction accuracies are acceptable. However, without fine-tuning or retraining, these applied machine learning algorithms are not able to reasonably predict outcomes for out-of-sample data (e.g., different types of work zone and work zone activities from other states).

2.1.2.2 Microsimulation. To properly evaluate the impact of different work zone activities on highway mobility using deterministic and stochastic models, a large amount of data from various work zone TCSs is required. In the absence of such data, microsimulation models such as VISSIM (Jehn & Turochy, 2019; Kan et al., 2014; Yeom et al., 2016; Zhang et al., 2020), CORSIM (Heaslip et al., 2011), and cellular automaton (Meng & Weng, 2011) has been widely applied in evaluating the impact of work zone TCSs (Mashhadi et al., 2021). These microsimulation modules have evaluated a variety of geometric, traffic, and environmental features from the perspectives of mobility and safety.

2.2 Current Practices Using Rolling Slowdowns and Research Related to Rolling Slowdowns

As an alternative to the full closure strategy, the rolling slowdown has been extensively applied for short term construction work. Examples of state policies implementing rolling slowdown are summarized below.

1. Traffic pacing guidelines. Missouri DOT and Florida DOT developed procedures to calculate the pacing speed, pacing distance, maximum queue, and total work time allowed for rolling slowdown implementation guidelines (FDOT, 2018; FHWA, 2019; INDOT, 2017).
2. Portable changeable messages signs (PCMS). The PCMS should be placed at the upstream of the exit to alert the drivers to downstream conditions during rolling slowdown operations (INDOT, 2017; WSDOT, 2021).

Although the rolling slowdown strategy has been widely used in some states, there is a paucity of literature quantifying the safety and operational benefits of the rolling slowdown compared with other traffic control strategies in construction areas. To the best of our knowledge, only one research paper (Saha & Kobryn, 2021) compared rolling slowdown and road closure from perspectives of safety, mobility and cost-effectiveness. Two locations for rolling slowdown and one site for road closure were selected in the case study from Fort Wayne, Indiana. Preliminary results indicated that the rolling slowdown caused lower disruption in the traffic than a road closure from the mobility point of view. Moreover, the implementation costs of rolling slowdown and road closure were almost equivalent. Nevertheless, the safety benefits of rolling slowdown and road closure were not quantified due to the lack of crash data (Saha & Kobryn, 2021).

3. RESEARCH METHODOLOGY

Rolling slowdowns were compared with temporary full closures on the interstate network, from both the safety and mobility standpoints. The analysis safety metrics and mobility simulation are described below.

3.1 Safety Analysis

First, the INDOT dashboard was used to search for trajectories that could be rolling slowdown operations. Then, the search results were confirmed using INDOT's interstate cameras. The results provided five rolling slowdown cases. To make valid comparisons, the same roadway segments (+/-10 miles) within which the rolling slowdowns took place were also searched for full closures. Since there were no planned closures during the data collection period (2020–2021) on/close to these segments, five cases of temporary full closures due to crashes were used instead. Finally, the INDOT dashboard was used to obtain hard braking events and relative velocities for all cases.

3.1.1 Hard Braking Events

Hard braking rates are used to compare rolling slowdowns to full closures. A hard braking event is defined as any vehicle decelerations greater than 8.76 ft/s^2. Hard braking rates are an emerging surrogate safety measure (SSM) applied in interstate and intersection safety studies and are directly related to crash rates. Approximately one crash/mile for every 147 hard-braking events occurs in and around interstate work zones (Desai et al., 2021). Five rolling slowdown cases were chosen for this study; all cases occurred on Indiana's interstate system in 2020–2021. First, speed profile maps for the five cases were obtained using the Indiana Performance Measures Dashboard, which contains connected vehicles' trajectory data. Next, hard-braking events were obtained from those maps. These maps show the time and location where the hard-braking events occurred. A hard-braking event is any vehicle decelerating at a rate greater than 8.76 ft/s^2. Figure 3.3 shows an example of the speed profile maps, with hard-braking events represented as red dots. Finally, the obtained total number of hard-braking events was normalized per traffic volume and total time using Equation 3.1.

$$\textit{Hard Braking Event} = \frac{\#\ of\ hard\ braking\ vehicles}{event\ time\ (hr) * \frac{volume\ (vehs)}{1{,}000}} \quad \text{(Equation 3.1)}$$

To compare rolling slowdowns with full closures, the dashboard dataset was searched for temporary full closures at or near the exact locations of the five cases of rolling slowdowns, all of which were full closures due to crashes. Information on the rolling slowdown and temporary full closure cases used in the comparison are presented in Table 3.1.

3.1.2 Rolling Slowdown and Full Closure Shockwave Formation and Dissipation

From the speed profile maps, the front and back of the queue of the five cases were analyzed. In the rolling slowdown cases, the front would be the lead vehicles, most likely police escort vehicles, and the back of the queue would be the back-most point of traffic accumulating behind the rolling slowdown vehicles, that is, the point at which new vehicles join the queue. In addition to identifying the hard-braking events, three values were extracted, as seen in Figure 3.1.

1. Front-of-queue speed
2. Back-of-queue speed (recovery wave or shockwave)
3. Relative velocity, which is the speed change a vehicle will undergo to merge to the back of the queue

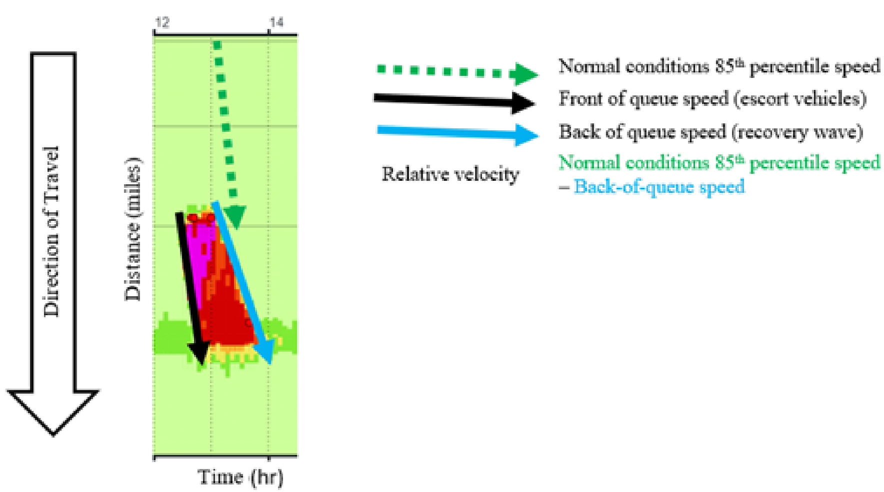


Figure 3.1 Shockwave analysis example.

3.2 Mobility and Simulation Environment

The impact of rolling slowdowns on interstate mobility was evaluated in terms of the total time of impact to travel time and was compared to that of temporary full closures. Rolling slowdowns were simulated using the following two different scenarios.

1. Applying different rolling slowdown speeds (changing the speed of escorting vehicles)
2. Applying rolling slowdowns during different times of the day (different traffic volume conditions)

PTV Vissim 11 was used to simulate the rolling slowdowns and the full closure scenarios, simulation location was along I-65 Northbound. Table 3.2 provides the legal description of the selected area where the simulated roadway work requiring a traffic stoppage occurs (for both rolling slowdowns and temporary full closure).

3.2.1 Simulation Environment Calibration

Traffic volumes, vehicle classifications, and speed profiles for the selected location for the study simulation were obtained for August 23, 2021, using the Indiana Department of Transportation (INDOT) interactive data maps MS2 (See Appendix A). The obtained data were used to build a simulation environment mirroring the events of August 23, 2021, along I-65 NB. The simulation environment was then assessed using the GEH factor (Equation 3.2) to determine the accuracy of the built model, and a value below five was considered accurate (Dowling et al., 2004).

$$GEH_i = \sqrt{\frac{2(m-c)^2}{m+c}} \qquad \text{(Equation 3.2)}$$

Where,
m: actual traffic volume for time step i.
c: simulation traffic volume for time step i.

TABLE 3.1
Rolling Slowdown and Temporary Full Closure Information

	Rolling Slowdown	Temporary Full Closure
Case 1 INTERSTATE 74	Thursday, June 4, 2020 Three back-to-back rolling slowdowns in each direction starting at 9:40 AM between mile markers 115 and 125 on the Eastbound and 125 and 135 on the Westbound	Friday, June 18, 2021 Full closure following a crash at 5:00 PM at mile marker 113 on the Westbound
Case 2 INTERSTATE 65	Sunday, July 26, 2020 Rolling slowdown starting at 12:30 PM between mile markers 164 and 170 on the Southbound	Sunday, May 9, 2021 Full closure following a crash at 10:10 AM at mile marker 175 on the Southbound
Case 3 INTERSTATE 65	Saturday, September 12, 2020 Rolling slowdown starting at 9:00 PM between mile markers 80 and 87 on the Southbound	Saturday, October 3, 2020 Full closure following a crash at 12:00 PM at mile marker 87 on the Southbound
Case 4 INTERSTATE 70	Thursday, June 24, 2021 Rolling slowdown starting at 8:00 PM between mile markers 90 and 94 on the Eastbound	Wednesday, June 3, 2020 Full closure following a crash at 7:00 PM at mile marker 78 on the Westbound
Case 5 INTERSTATE 65	Friday, August 6, 2021 Four back-to-back rolling slowdowns at 12:00 AM between mile markers 207 and 220 on the Southbound	Tuesday, September 14, 2021 Full closure following a crash at 6:00 PM at mile marker 240 on the Northbound

TABLE 3.2
Simulated Work Zone Location Description

Interstate	Township	N	W	Posted Speed Limit
INTERSTATE 65	Prairie Township, Indiana	40°36′01.21″	86°58′32.45″	SPEED LIMIT 70

Figure 3.2 shows the computed GEH factor for each hour of the simulated day.

3.2.2 Rolling Slowdowns

The simulated rolling slowdowns were designed per the FHWA *Guidelines on Rolling Roadblocks for Work Zone Applications* (ATSSA, 2013). Total pacing distance, pacing clearance distance, and work pacing distance, seen in Figure 3.4, were calculated using Equations 3.3–3.5:

$$L = \frac{t_w}{60} S_p \left(\frac{S_p}{S_r - S_p} + 1 \right) \qquad \text{(Equation 3.3)}$$

$$L_c = \frac{\left(\left(\frac{t_w}{60} \right) * S_p^2 \right)}{S_r - S_p} \qquad \text{(Equation 3.4)}$$

$$L = L_c + L_w \qquad \text{(Equation 3.5)}$$

Where,

L = total pacing distance (miles), with maximum pacing operation length of 10 miles.

L_c = distance pacing vehicles travel to clear the road of any vehicles traveling at regulatory speed/posted speed limit (miles).

L_w = distance pacing vehicles travel while work is being performed downstream (miles).

t_w = duration of work (minutes), with maximum allowed work duration of 30 minutes.

S_p = pacing vehicles speed (mph), with minimum speed allowed of 10 mph.

S_r = regulatory speed/posted speed limit (mph).

3.2.2.1 Varying work zone duration and rolling speed. The study simulated a range of scenarios encompassing

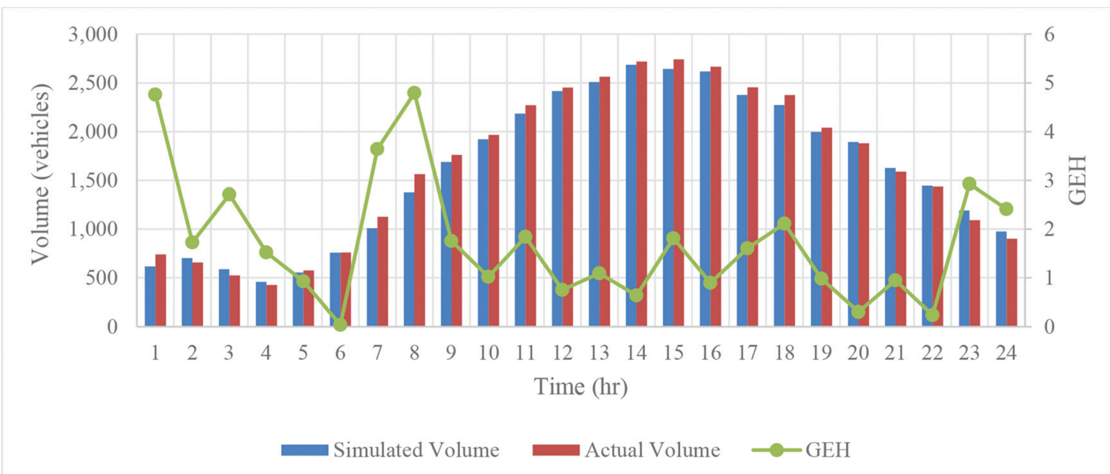


Figure 3.2 Simulation calibration measure.

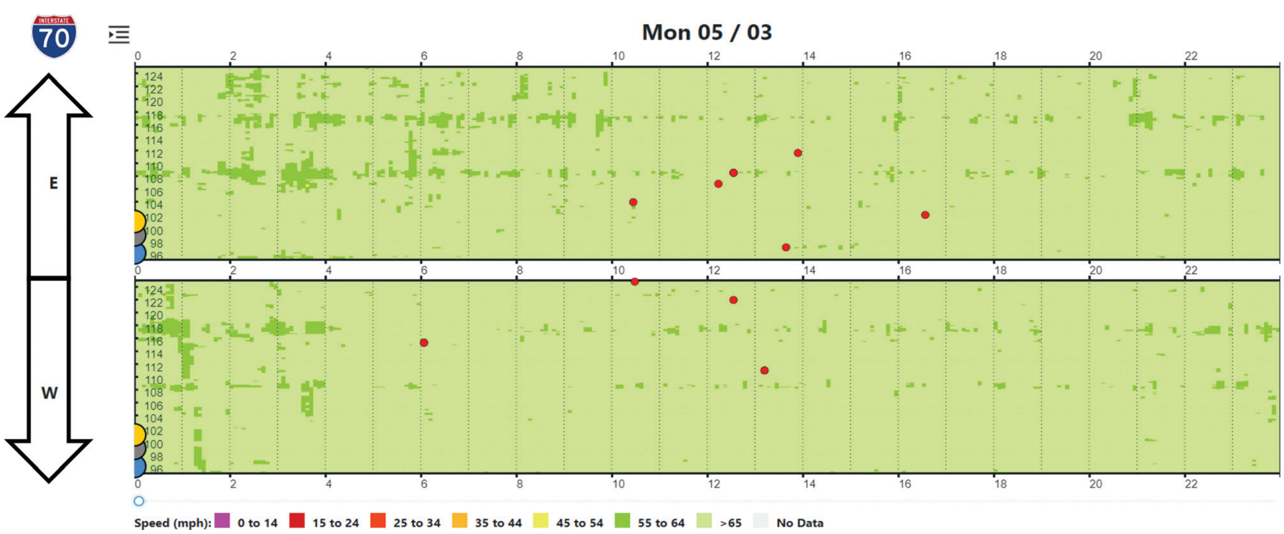


Figure 3.3 Speed profile map of I-70 on Monday 05/03/2021 with hard-braking events in red (y-axis: mile marker, x-axis: time of day).

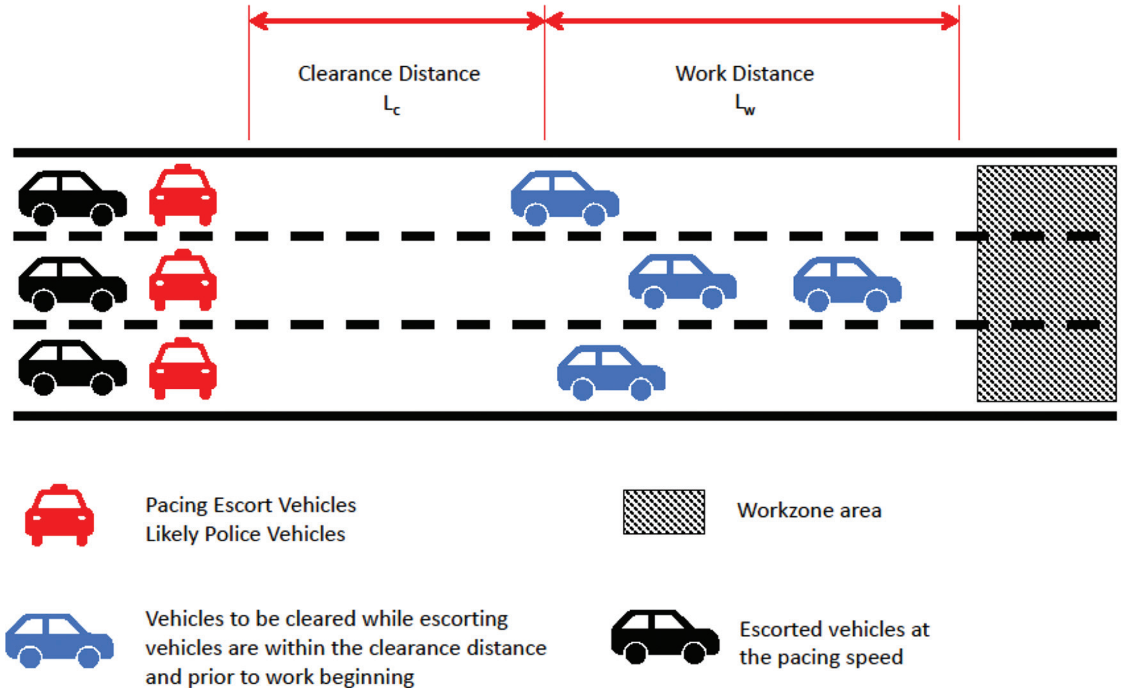


Figure 3.4 Rolling slowdown distances.

different rolling slowdown speeds and work durations along the I-65 study segment. Table 3.3 lists the scenarios examined. Scenarios exceeding the *FHWA Guidelines for Total Pacing Operation Length*, shown in red were excluded from the analysis.

3.2.2.2 Rolling slowdowns during different times of the day. The impact of varying traffic volumes on the efficiency of rolling slowdowns was examined by performing rolling slowdowns during different times of the day. Six trials of rolling slowdown simulations were tested. Table 3.4 provides the times at which the simulation environment applied rolling slowdowns. Each trial included the scenarios listed in Table 3.4 to assess the impact of varying rolling slowdown speeds, work zone duration, and corresponding existing traffic volumes at different times of the day resulting in a total of 54 simulation runs.

3.2.3 Temporary Full Closures

A temporary full closure was simulated at the location described in Table 3.2. The simulated temporary full closure used three different work zone durations—10, 20, and 30 minutes, resulting in 18 simulation runs. The simulated work durations were then compared to the rolling slowdown scenarios analyzed in Table 3.3 in terms of vehicles' total travel time and duration to dissipate and return to normal travel times.

TABLE 3.3
Considered Rolling Slowdown Simulation Input Variables

Pacing Speed (mph)	Work Duration (min)	L	L_c	L_w
10	30	5.83	0.83	5.00
	20	3.89	0.56	3.33
	10	1.94	0.28	1.67
20	30	14.00	4.00	10.00
	20	9.33	2.67	6.67
	10	4.67	1.33	3.33
30	30	26.25	11.25	15.00
	20	17.50	10.00	7.50
	10	8.75	3.75	5.00

Note: Red text indicates scenarios that exceeded the *FHWA Guidelines for Total Pacing Operation Length* and were therefore excluded from the analysis.

TABLE 3.4
Rolling Slowdown Simulated Time of the Day

Trial	Rolling Slowdown Start Time
1	2:30 AM
2	6:30 AM
3	10:30 AM
4	14:30 PM
5	18:30 PM
6	22:30 PM

4. RESULTS

4.1 Safety Results

Five rolling slowdown and full closure cases were chosen for this study, all performed on Indiana's interstate system in 2020 and 2021. Figure 4.1 shows the location of the five cases, with green points representing rolling slowdowns and red points for the full closures. Tables 4.1–4.5 provide the details for all cases evaluated.

Generally, rolling slowdowns had either stationary or moving forward shockwaves. In contrast, full closures always had backward moving shockwaves.

In the case of the rolling slowdowns, the average shockwave velocity was 12.68 mph moving the same direction of travel (forward-moving shockwave). The average relative velocity was 67.2 mph, and the average hard-braking events were at a rate of 2.46 HB/1,000 veh/hr.

The average shockwave velocity was -6.54 mph in case of the full closures, moving in the opposite direction of travel (backward-moving shockwave). The average relative velocity was 84.34 mph, and the average hard-braking events were at a rate of 9.07 HB/1,000 veh/hr.

The speed profile maps, shockwave velocity, relative velocity, and hard-braking events for each analyzed case are described in Sections 4.1.1–4.1.5.

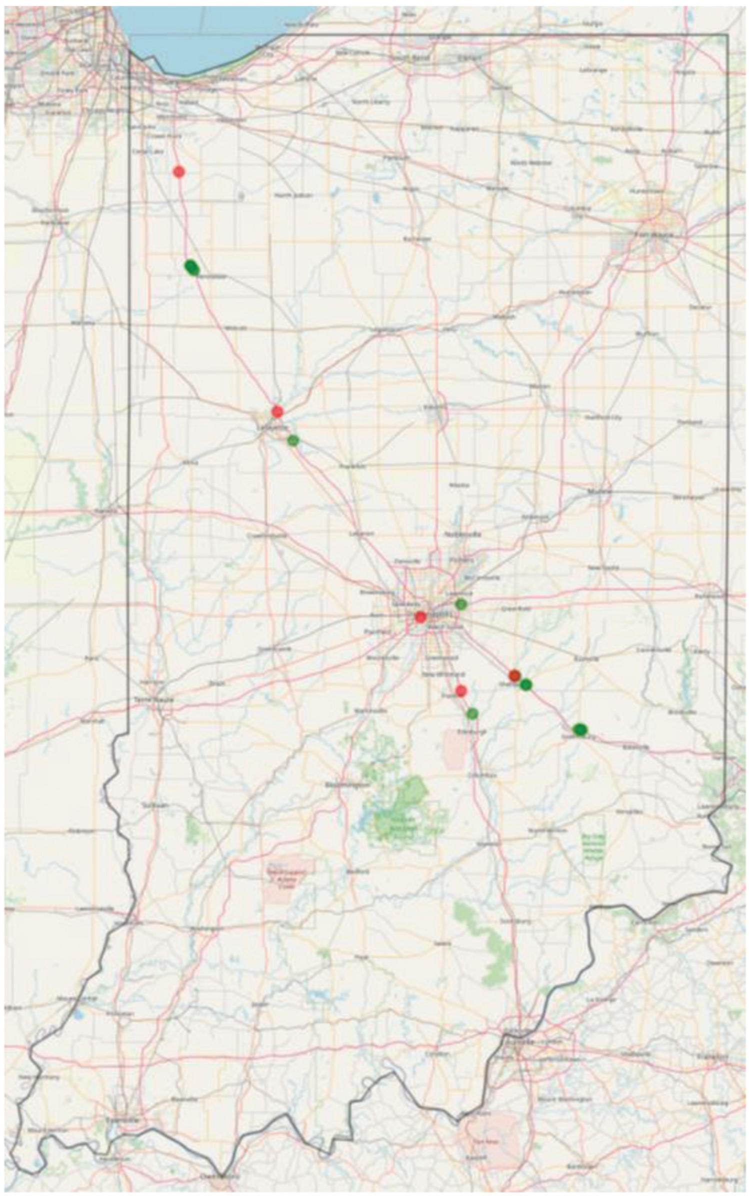
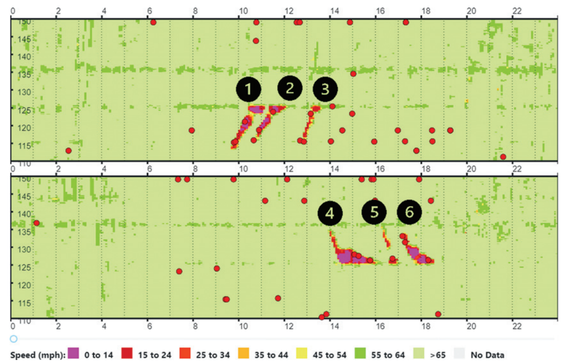
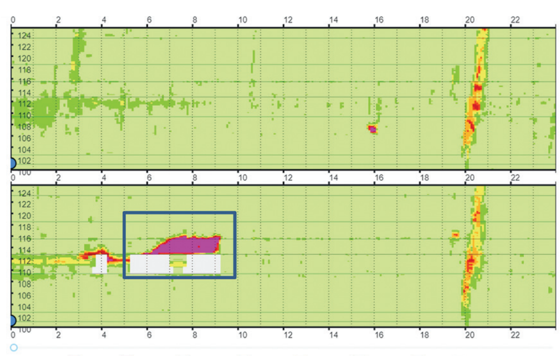


Figure 4.1 Location of rolling slowdowns (green) and full closures (red).

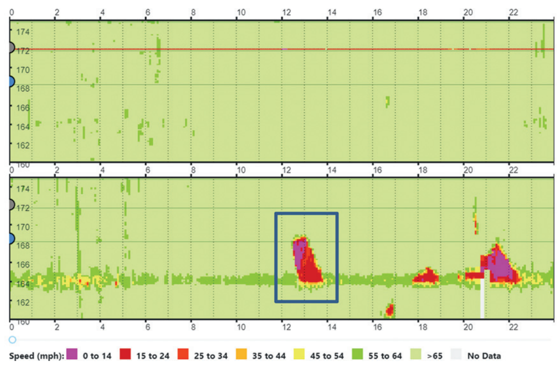
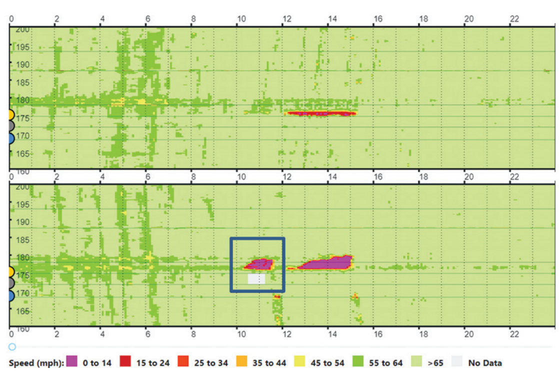
4.1.1 Case 1 Interstate 74

TABLE 4.1
Case 1 Safety Analysis

Rolling Slowdown	
Date, time, and location	Thursday, June 4, 2020 Three back-to-back rolling slowdowns in each direction starting at 9:40 AM between mile markers 115 and 125 on the Eastbound and 125 and 135 on the Westbound
Heat map	
Normal Condition 85th Percentile Speed (mph) = 79 mph	
Front of queue speed (mph)	(1) $V_{rolling}$ = 23.93 mph (2) $V_{rolling}$ = 16.08 mph (3) $V_{rolling}$ = 15.65 mph (4) $V_{rolling}$ = 22.38 mph (5) $V_{rolling}$ = 11.98 mph (6) $V_{rolling}$ = 21.50 mph
Back of queue speed (mph)	(1) $V_{recovery}$ = 22.60 mph (2) $V_{recovery}$ = 13.70 mph (3) $V_{recovery}$ = 14.80 mph (4) $V_{recovery}$ = 10.76 mph (5) $V_{recovery}$ = 13.25 mph (6) $V_{recovery}$ = 9.58 mph
Relative velocity (mph)	(1) V = 56.40 mph (2) V = 65.30 mph (3) V = 64.20 mph (4) V = 68.24 mph (5) V = 65.75 mph (6) V = 69.43 mph
Hard-braking	(1) 2.87 HB/1000 veh/hr (2) 4.86 HB/1000 veh/hr (3) 9.91 HB/1000 veh/hr (4) 1.29 HB/1000 veh/hr (5) 6.37 HB/1000 veh/hr (6) 1.39 HB/1000 veh/hr
Full Closure	
Date, time, and location	Friday, June 18, 2021 Full closure following a crash at 5:00 PM at mile marker 113 on the Westbound
Heat map	
Normal Condition 85th Percentile Speed (mph) = 79 mph	
Back of queue speed (mph)	$V_{shockwave}$ = 7.87 mph
Relative velocity (mph)	86.87 mph
Hard-braking	2.80 HB/1,000 veh/hr

4.1.2 Case 2 Interstate 65

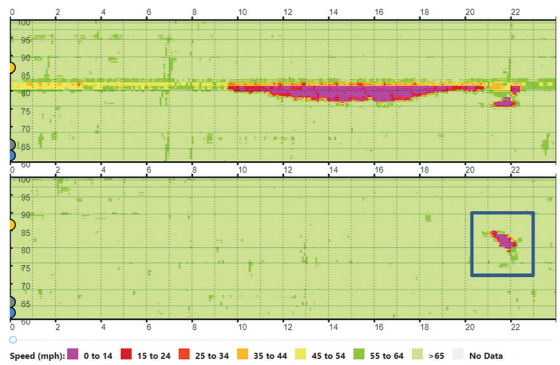
TABLE 4.2
Case 2 Safety Analysis

Rolling Slowdown	
Date, time, and location	Sunday, July 26, 2020 Rolling slowdown starting at 12:30 PM between mile markers 164 and 170 on the Southbound
Heat map	
Normal Condition 85th Percentile Speed (mph) = 69 mph	
Front of queue speed (mph)	$V_{rolling}$ = 10.93 mph
Back of queue speed (mph)	$V_{recovery}$ = 11.83 mph
Relative velocity (mph)	57.18 mph
Hard-braking	0.93 HB/1,000 veh/hr
Full Closure	
Date, time, and location	Sunday, May 9, 2021 Full closure following a crash at 10:10 AM at mile marker 175 on the Southbound
Heat map	
Normal Condition 85th Percentile Speed (mph) = 79 mph	
Back of queue speed (mph)	$V_{shockwave}$ = 6.30 mph
Relative velocity (mph)	75.30 mph
Hard-braking	12.70 HB/1,000 veh/hr

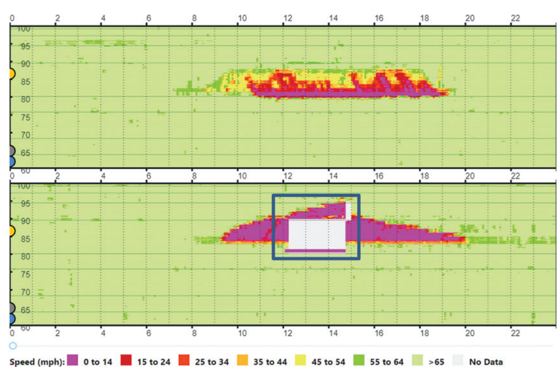
4.1.3 Case 3 Interstate 65

TABLE 4.3
Case 3 Safety Analysis

Rolling Slowdown	
Date, time, and location	Saturday, September 12, 2020 Rolling slowdown starting at 9:00 PM between mile markers 80 and 87 on the Southbound
Heat map	



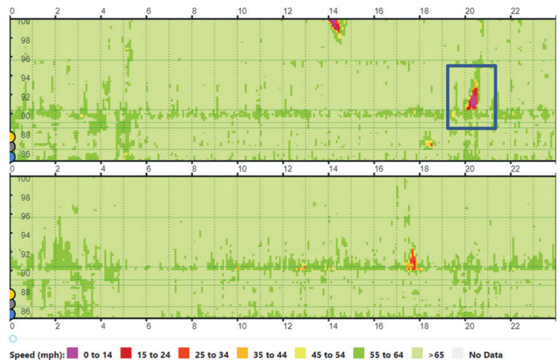
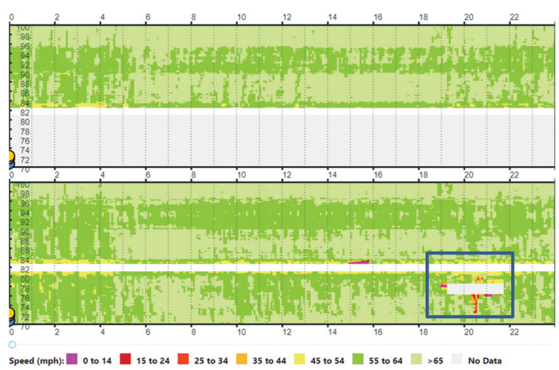
Normal Condition 85th Percentile Speed (mph) = 77 mph	
Front of queue speed (mph)	$V_{rolling}$ = 14.13 mph
Back of queue speed (mph)	$V_{recovery}$ = 6.95 mph
Relative velocity (mph)	70.05 mph
Hard-braking	0 HB/1,000 veh/hr
Full Closure	
Date, time, and location	Saturday, October 3, 2020 Full closure following a crash at 12:00 PM at mile marker 87 on the Southbound
Heat map	



Normal Condition 85th Percentile Speed (mph) = 77 mph	
Back of queue speed (mph)	$V_{shockwave}$ = -11.30 mph
Relative velocity (mph)	88.30 mph
Hard-braking	2.25 HB/1,000 veh/hr

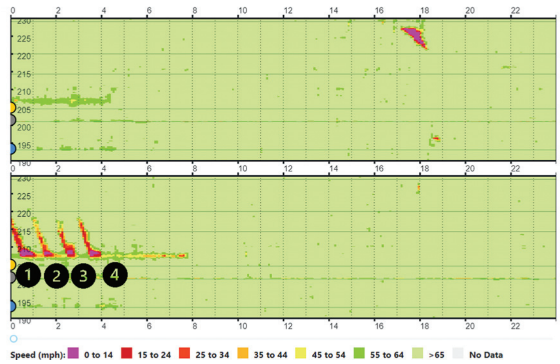
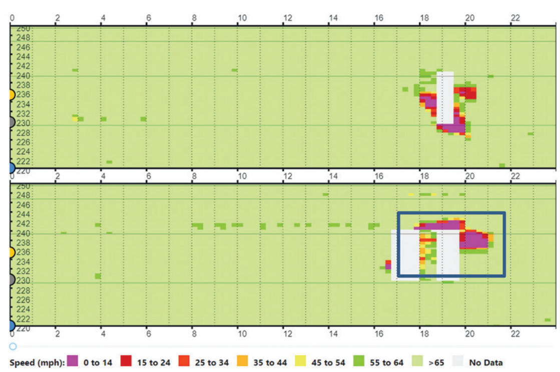
4.1.4 Case 4 Interstate 70

TABLE 4.4
Case 4 Safety Analysis

Rolling Slowdown	
Date, time, and location	Thursday, June 24, 2021 Rolling slowdown starting at 8:00 PM between mile markers 90 and 94 on the Eastbound
Heat map	
Normal Condition 85th Percentile Speed (mph) = 87 mph	
Front of queue speed (mph)	$V_{rolling}$ = 7.60 mph
Back of queue speed (mph)	$V_{recovery}$ = 6.53 mph
Relative velocity (mph)	80.48 mph
Hard-braking	1.86 HB/1,000 veh/hr
Full Closure	
Date, time, and location	Wednesday, June 3, 2020 Full closure following a crash at 7:00 PM at mile marker 78 on the Westbound
Heat map	
Normal Condition 85th Percentile Speed (mph) = 87 mph	
Back of queue speed (mph)	$V_{shockwave}$ = -2.6 mph
Relative velocity (mph)	89.6 mph
Hard-braking	10.947 HB/1,000 veh/hr

4.1.5 Case 5 Interstate 65

TABLE 4.5
Case 5 Safety Analysis

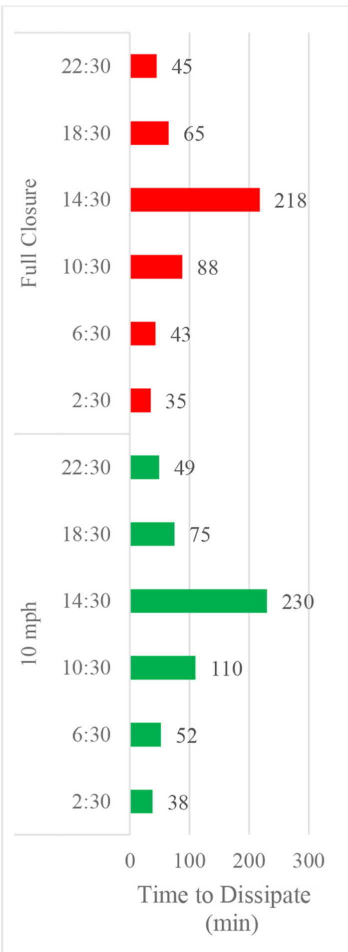
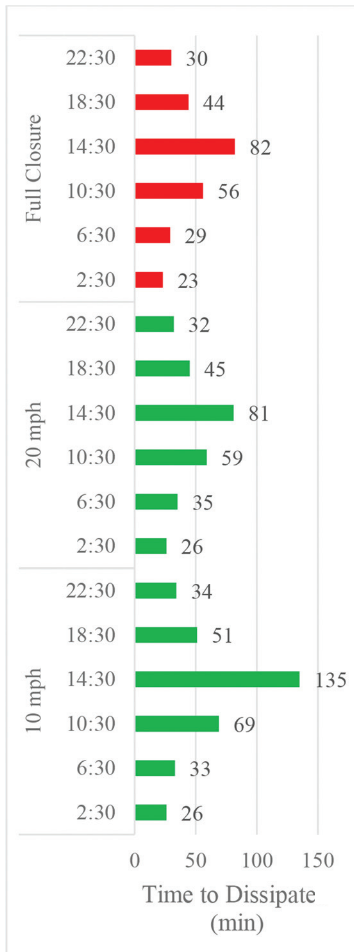
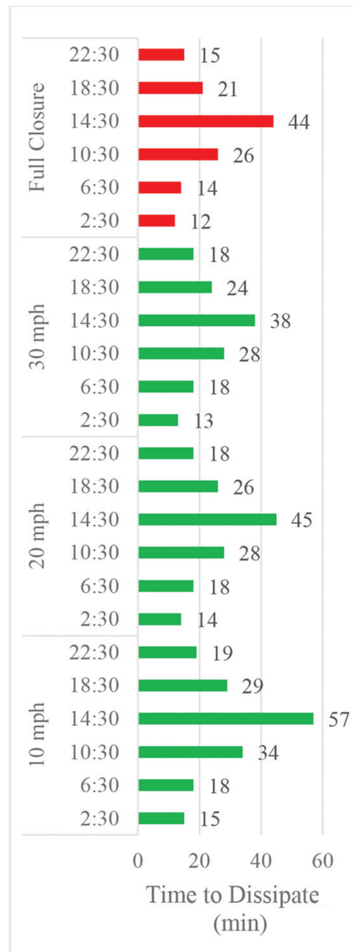
Rolling Slowdown	
Date, time, and location	Friday, August 6, 2021 Four back-to-back rolling slowdowns at 12:00 AM between mile markers 207 and 220 on the Southbound
Heat map	
Normal Condition 85th Percentile Speed (mph) = 77 mph	
Front of queue speed (mph)	❶ $V_{rolling}$ = 22.83 mph ❷ $V_{rolling}$ = 26.30 mph ❸ $V_{rolling}$ = 24.55 mph ❹ $V_{rolling}$ = 26.08 mph
Back of queue speed (mph)	❶ $V_{recovery}$ = 12.94 mph ❷ $V_{recovery}$ = 12.39 mph ❸ $V_{recovery}$ = 22.40 mph ❹ $V_{recovery}$ = 22.18 mph
Relative velocity (mph)	❶ V = 64.06 mph ❷ V = 64.61 mph ❸ V = 54.60 mph ❹ V = 65.26 mph
Hard-braking	❶ 0 HB/1000 veh/hr ❷ 2.56 HB/1000 veh/hr ❸ 0 HB/1000 veh/hr ❹ 0 HB/1000 veh/hr
Full Closure	
Date, time, and location	Wednesday, June 3, 2020 Full closure following a crash at 7:00 PM at mile marker 78 on the Westbound
Heat map	
Normal Condition 85th Percentile Speed (mph) = 77 mph	
Back of queue speed (mph)	$V_{shockwave}$ = -4.63 mph
Relative velocity (mph)	81.63 mph
Hard-braking	16.67 HB/1,000 veh/hr

4.2 Mobility Results

Three work zone durations were simulated at six different times of the day for full closures while rolling slowdowns were simulated using different lead-vehicle speeds for the actual scenarios. The total time from the beginning of work till the time traffic entirely dissipates and returns to normal conditions is listed in Table 4.6, with full closures in red and rolling slowdowns in green.

Except for two cases, it is observed that full closures tend to have shorter impact durations on travel times as compared to rolling slowdowns. In addition, and for both strategies, as the work duration increases from 10 minutes to 20 minutes, the impact on travel times nearly doubles. However, when the work duration increases to 30 minutes, the impact on travel times nearly quadruples, showing an exponential trend between the work duration and impact on travel times.

TABLE 4.6
Simulation Mobility Results

30-Minute Work Duration	20-Minute Work Duration	10-Minute Work Duration
		

5. CONCLUSIONS AND RECOMMENDATIONS

When traffic lanes through a work zone need to be kept clear of traffic to accommodate short-term activities, such as placing overhead beams and erecting overhead signs, rolling slowdowns can serve as an alternative to a full road closure. Rolling slowdowns will provide up to 30 minutes to complete work activities without bringing approaching traffic to a complete stoppage. The selection of an appropriate work zone traffic control strategy should consider both the safety and mobility of roadway users and site workers. While rolling slowdowns have been applied in several states, the advantages and disadvantages have yet to be investigated. Thus, the objective of this study was to determine the most appropriate temporary traffic control strategy to use under specified circumstances, more specifically, in terms of road users' safety and mobility.

5.1 Safety

This study used the relationship between relative velocities and hard braking rates to compare rolling slowdowns to full closures. Relative velocity is the change in speed a vehicle must undergo to merge into a group of vehicles; hard braking events are defined as vehicle decelerations greater than 8.76 ft/s^2. Hard braking rates are an emerging surrogate safety measure (SSM) applied in interstate and intersection safety studies and are directly related to crash rates. Approximately one crash/mile for every 147 hard-braking events occurs in and around interstate work zones (Desai et al., 2021).

This study found that rolling slowdowns cause lower relative velocity values and consequently lower hard braking rates than full closures because their resulting shockwaves move forward. However, a rolling slowdown operation may come to a temporary stop, when work downstream takes longer than anticipated. In such cases, the resulting shockwave would be expected to move backward, making the rolling slowdown operation lose its safety advantage. Hence, rolling slowdowns are beneficial when avoiding coming to a halt, to ensure that the forming shockwave moves forward, resulting in lower relative velocities and hence, lower hard braking rates.

On the other hand, in full closures where vehicles accumulate in a backward forming queue, that is, when a queue forms in the direction opposite to the direction of travel (backward forming shockwave), the braking dynamic would be more severe. Such closures result in higher relative velocities and hard-braking rates, thus making rolling slowdowns a safer option when compared to full closures.

Based on the five cases analyzed in this study, rolling slowdowns had an average wave velocity of 12.68 mph (moving forward - recovery wave), an average relative velocity of 67.22 mph, and an average hard-braking rate of 2.46 HB/1,000 veh/hr. On the other hand, full closures had an average wave velocity of -6.54 mph (backward moving shockwave), an average relative velocity of 84.34 mph, and an average hard-braking rate of 9.07 HB/1,000 veh/hr. Table 5.1 and Figure 5.1 compares the relative velocities and hard-braking rates of both traffic control strategies.

Full closures analyzed in this study were unplanned closures, implying that travelers had no early signage warnings. Early warning signs could help reduce relative velocities for planned closures but not to the extent of a rolling slowdown. The shockwave in full closures will always be expected to form in the opposite direction of travel (backward-moving shockwave). Therefore, it is hypothesized that full closures will have a backward moving shockwave (for both planned and unplanned closures) and, hence, consequently, high hard braking rates.

5.2 Mobility

The simulation environment results showed full closure, for most cases, as the superior alternative when compared to a rolling slowdown in terms of the total impact on travel times, as seen in Table 5.2. This, in part, is due to the additional time required for a rolling slowdown operation when the lead vehicles travel at pacing speed and before work begins at the work zone site (clearance distance as seen in Figure 3.4). This extra pacing distance must be traveled before work begins to ensure all vehicles at regulatory speed have exited the segment between the lead vehicle and the worksite and that all other vehicles are behind the lead vehicles. In comparison, full closure will close the road adjacent to the worksite. Hence, full closures will not require the added buffer of safety to ensure the exit of regulatory speed vehicles before the commencement of work zone activities.

Although full closures, for most cases, caused a lower impact on total travel times, this was only by a few minutes advantage compared to rolling slowdowns, as seen in Table 5.2. On the other hand, rolling slowdowns were safer for roadway users in terms of hard-braking

TABLE 5.1
Rolling Slowdown and Full Closure Comparison

	Rolling Slowdown	Full Closure
Average wave velocity (mph)	12.68 (forward moving)	-6.54 (backward moving)
Average relative velocity (mph)	67.22	84.34
Average hard braking rate (HB/1,000 veh/hr)	2.46	9.07

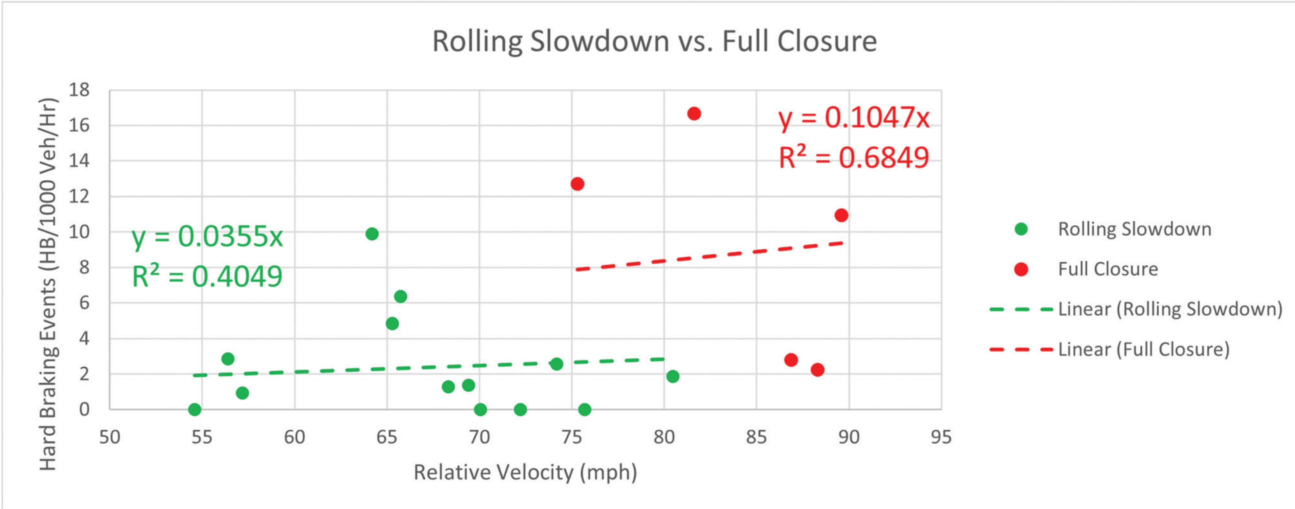


Figure 5.1 Safety comparison of rolling slowdown and full closure.

TABLE 5.2
Ideal Temporary Traffic Control in Terms of Travel Time and Time of Day

	2:30 AM	6:30 AM	10:30 AM	14:30 PM	18:30 PM	22:30 PM
30-minute work duration	Full closure	Full closure	Full closure	Full closure	Full closure	Full closure
20-minute work duration	Full closure	Full closure	Full closure	Rolling slowdown	Full closure	Full closure
10-minute work duration	Full closure	Full closure	Full closure	Rolling slowdown	Full closure	Full closure

rates as they consequently present lower probabilities of causing crashes.

It is recommended that overseeing authorities (i.e., DOT) should require designers, seeking the preferred MOT strategy, to provide a comprehensive description of their designs and to have all stakeholders (i.e., DOT, police, and contractors) involved in the review process, such plan can help in detecting and anticipating potential problems.

The mobility and safety analysis results show a tradeoff in which rolling slowdowns are safer yet impact travel times for longer durations than full closures, making it a typical transportation problem where either safety or mobility can be prioritized simultaneously. Furthermore, this research provides a new safety measure insight by introducing the relationship between relative velocities and hard braking rates. This relationship is beneficial when analyzing MOTs that require all lanes of travel to either come to a halt or to require vehicles in these lanes to travel at lower/higher speeds than vehicles upstream.

5.3 Future Work

In this study, planned rolling slowdowns were compared to unplanned full closures because the Indiana interstate had no planned closures during the data collection period (2020–2021). Future work should consider comparing planned closures to planned rolling slowdowns. In addition, the mobility analysis found rolling slowdowns minimally less advantageous than full closures regarding mobility and impact on travel times. However, the examined segment was a rural interstate with large ramp spacing. Future work should consider simulating an urban segment with short ramp spacing. The mobility impacts of rolling slowdowns will worsen in urban areas as all on-ramps within the rolling range/distance will be closed per the FHWA *Guidelines on Rolling Roadblocks for Work Zone Applications*. Future studies should also consider cost and logistics as rolling slowdowns may be disadvantageous as they often require collaboration between several entities (police, DOT, etc.), making it more challenging to implement on the go and perhaps more expensive.

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APPENDICES

Appendix A. I-65 Simulation Traffic Data

Appendix B. Rolling Slowdown FHWA Ranges

APPENDIX A. I-65 SIMULATION TRAFFIC DATA

Figure A.1 Simulated segment (I-65).

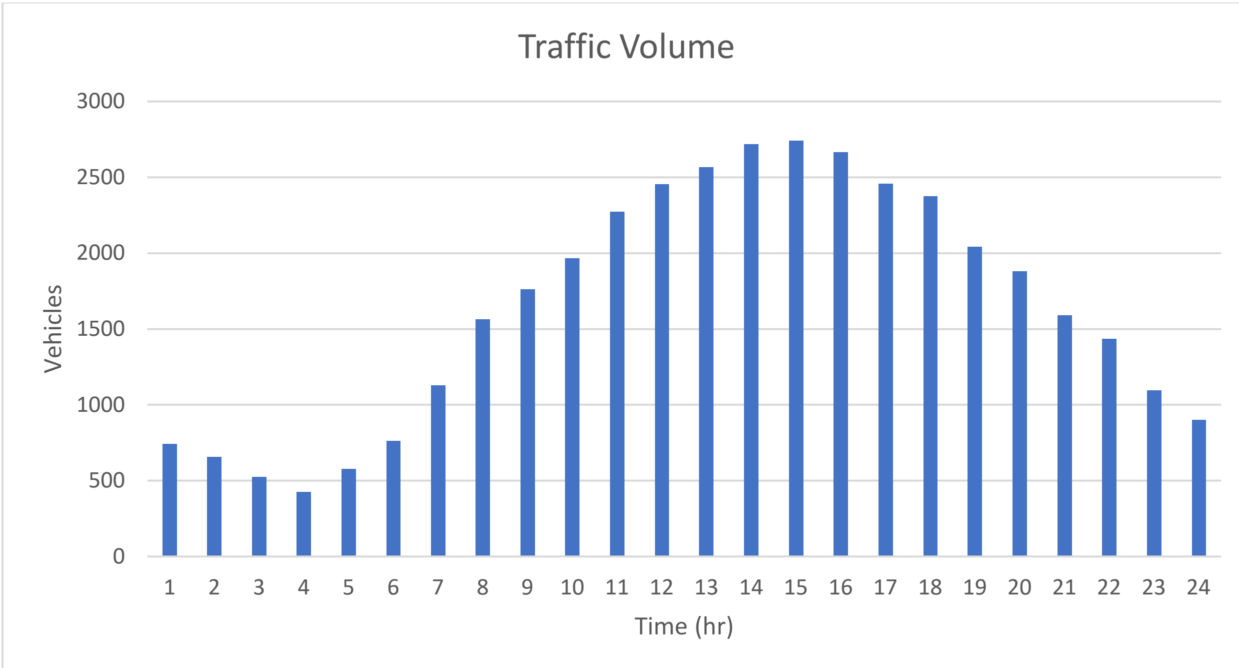

Figure A.2 I-65 Traffic volume.

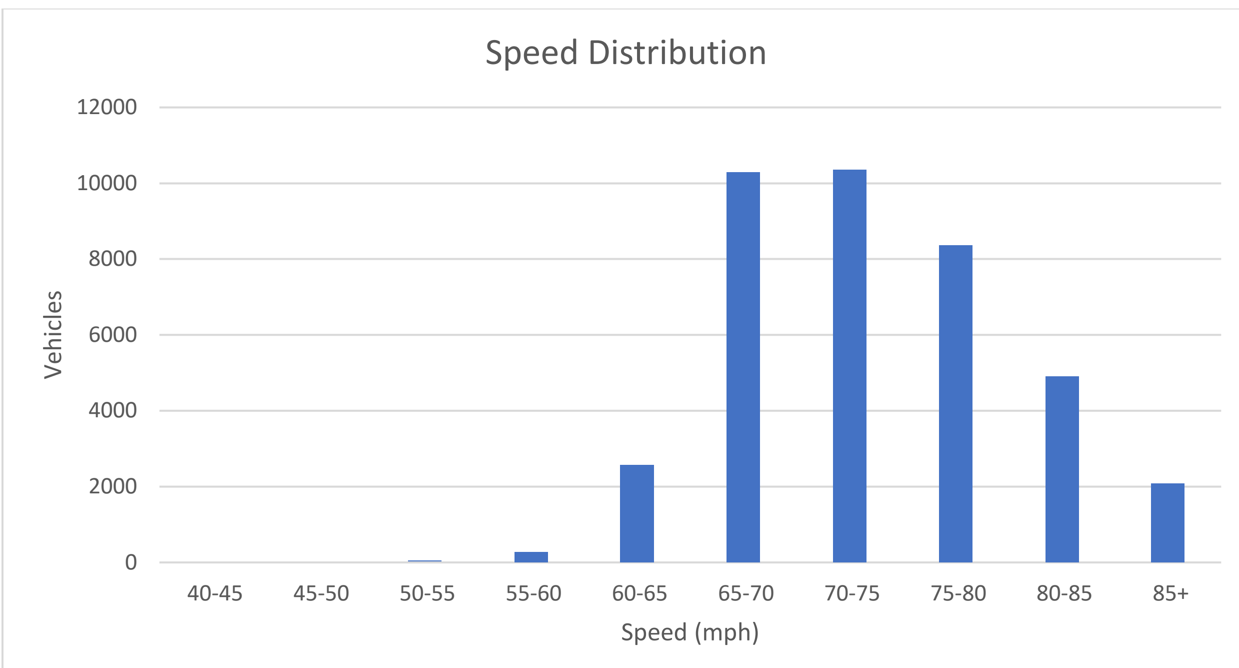

Figure A.3 I-65 speed distribution.

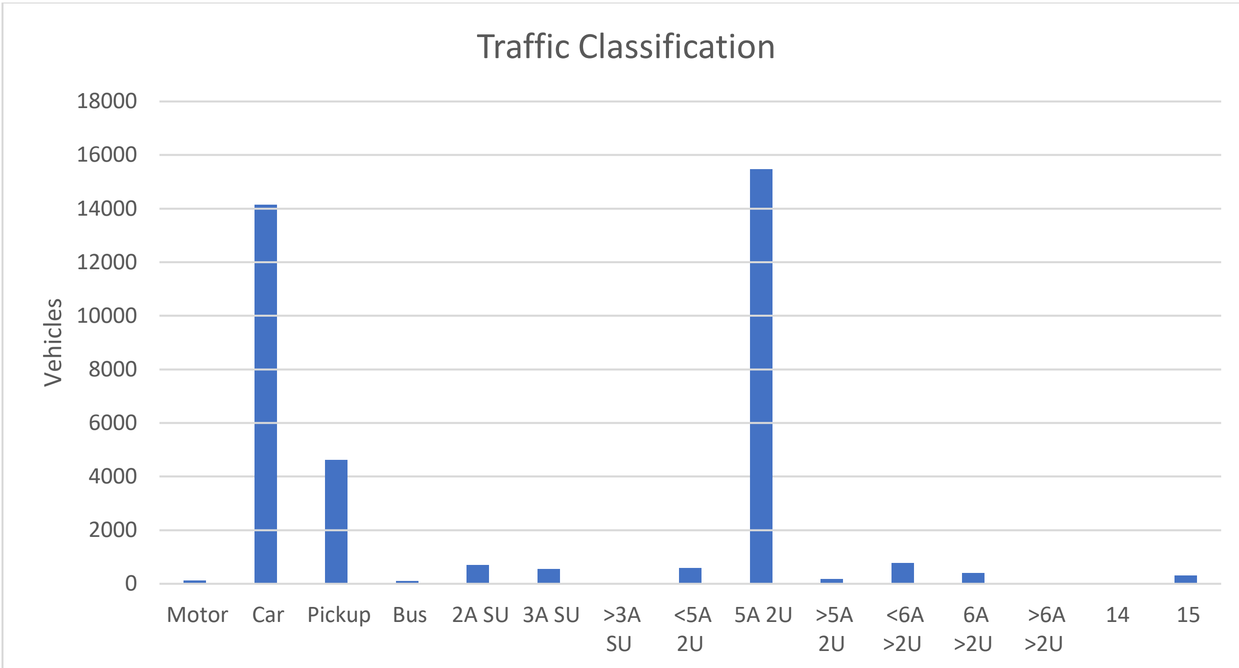

Figure A.4 I-65 vehicular classification.

APPENDIX B. ROLLING SLOWDOWN FHWA RANGES

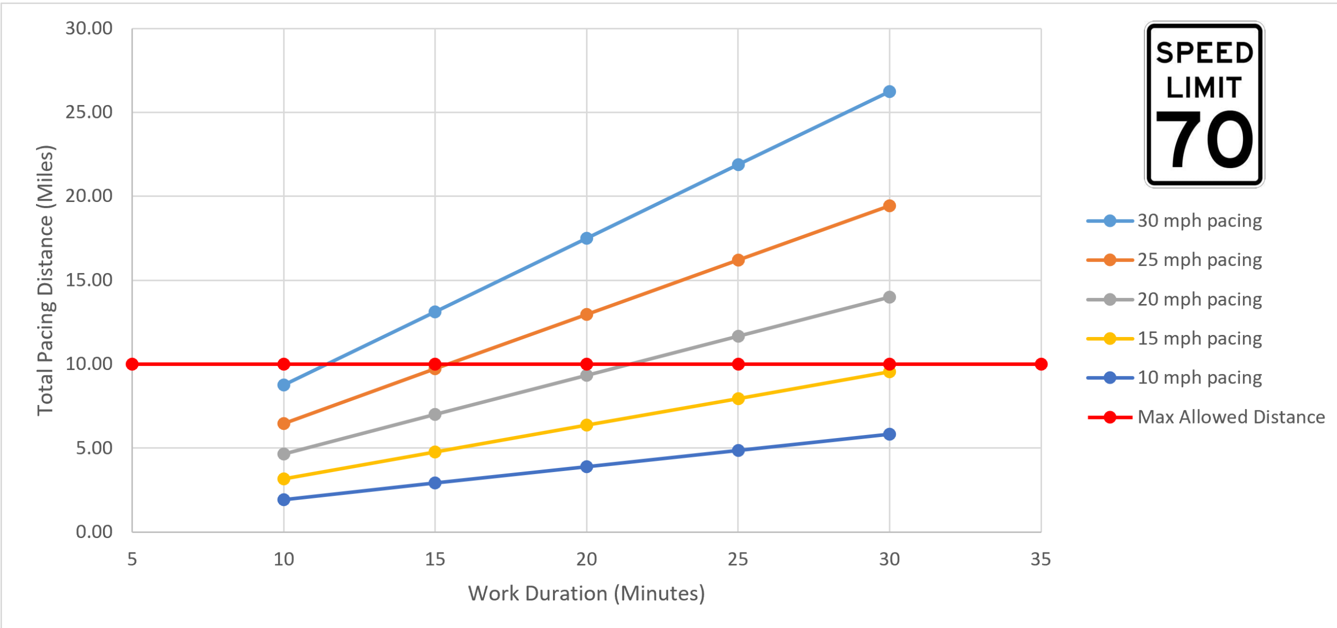

Figure B.1 Rolling slowdown ranges for 70 mph roads.

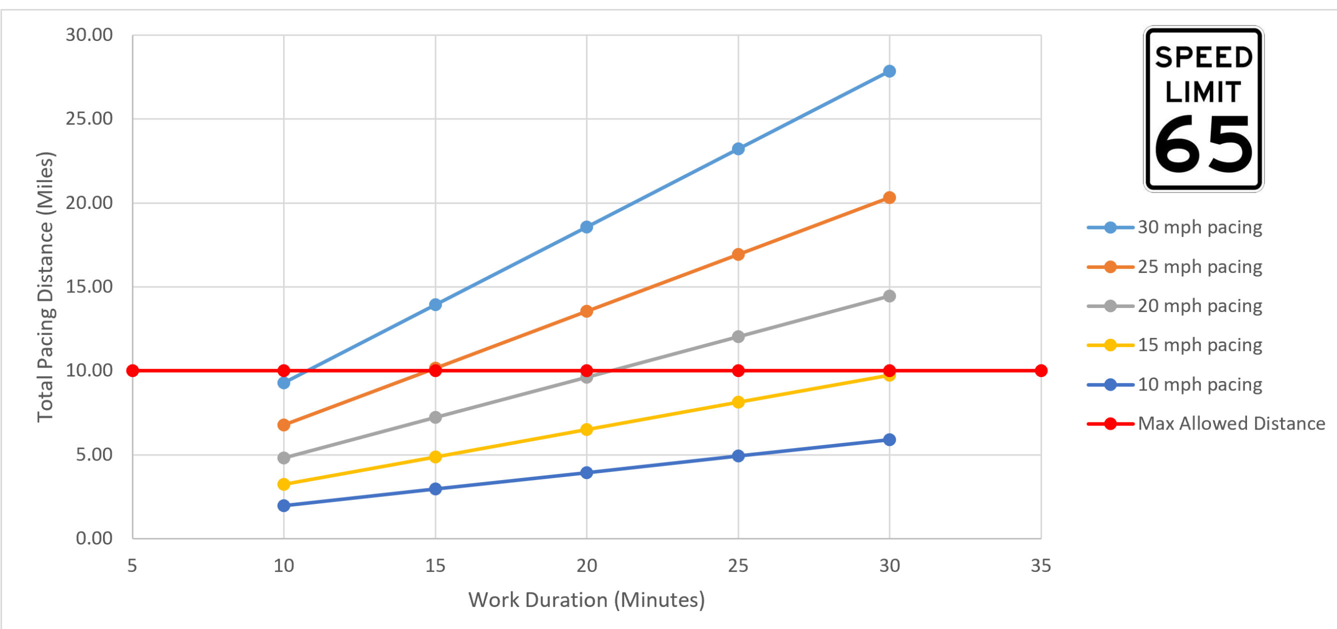

Figure B.2 Rolling slowdown ranges for 65 mph roads.

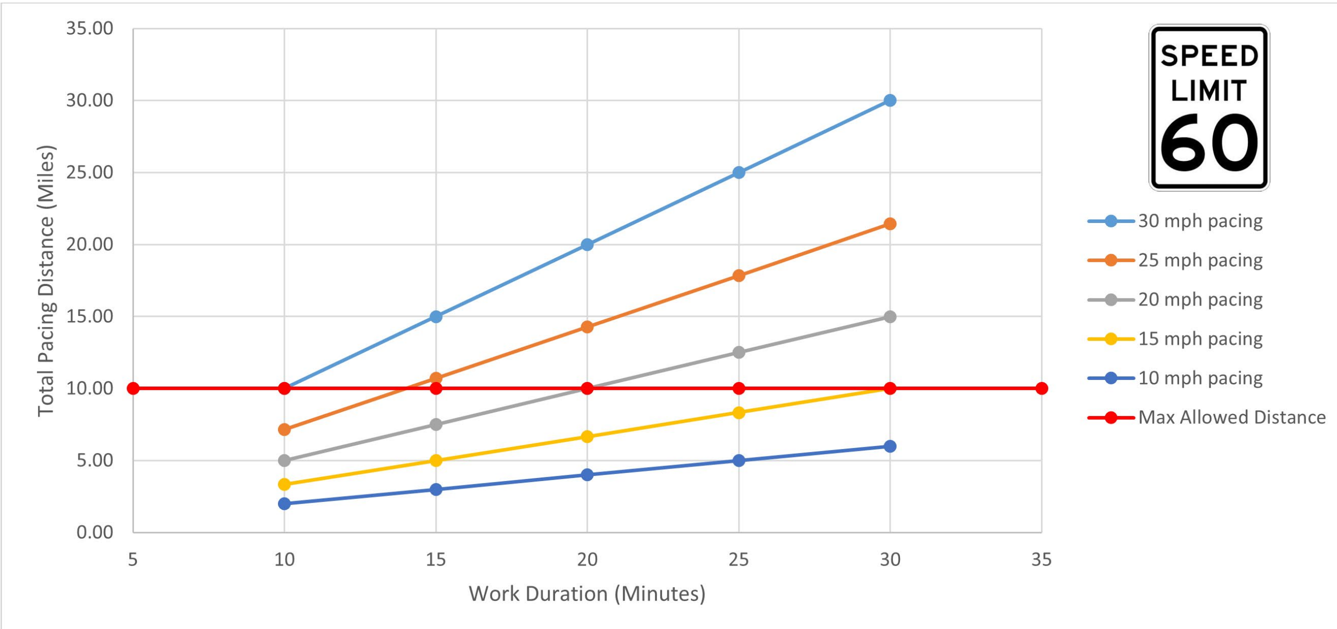

Figure B.3 Rolling slowdown ranges for 60 mph roads.

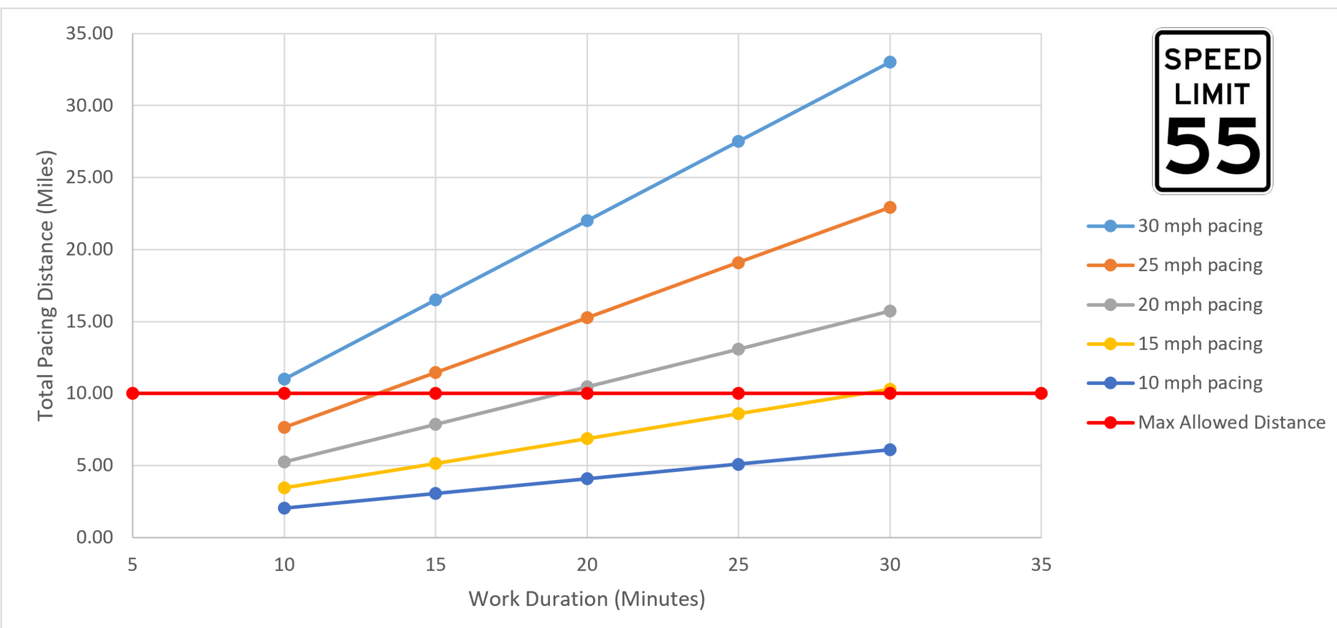

Figure B.4 Rolling slowdown ranges for 55 mph roads.

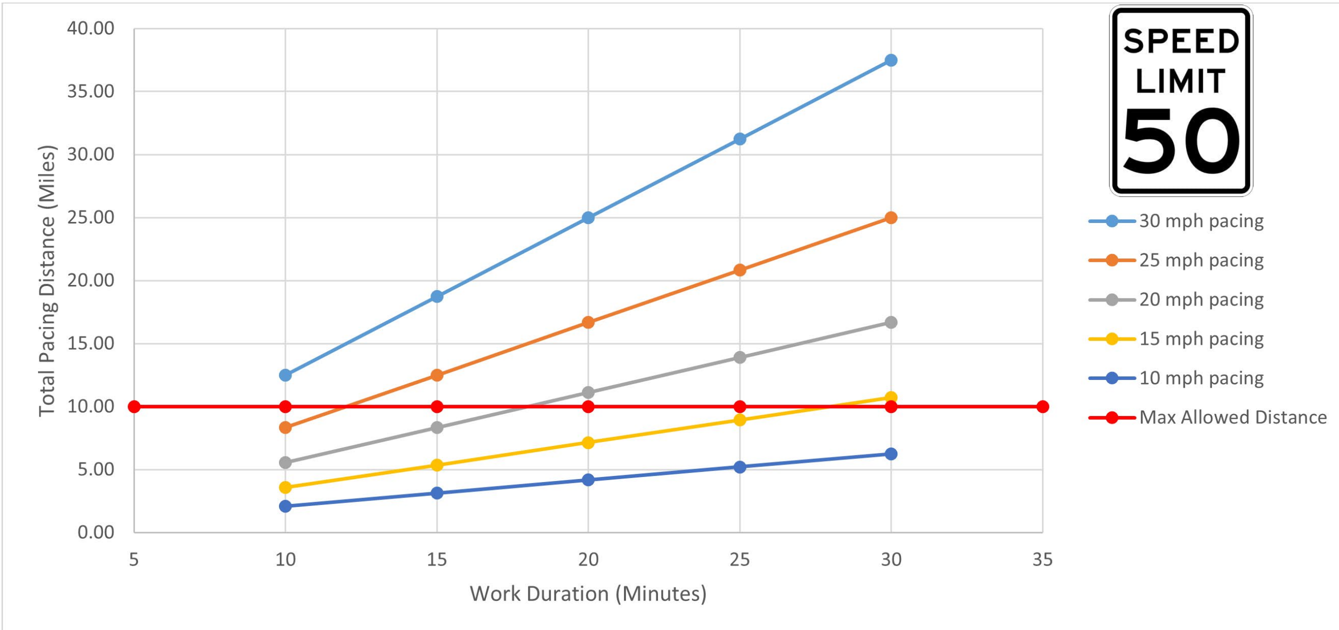

Figure B.5 Rolling slowdown ranges for 50 mph roads.

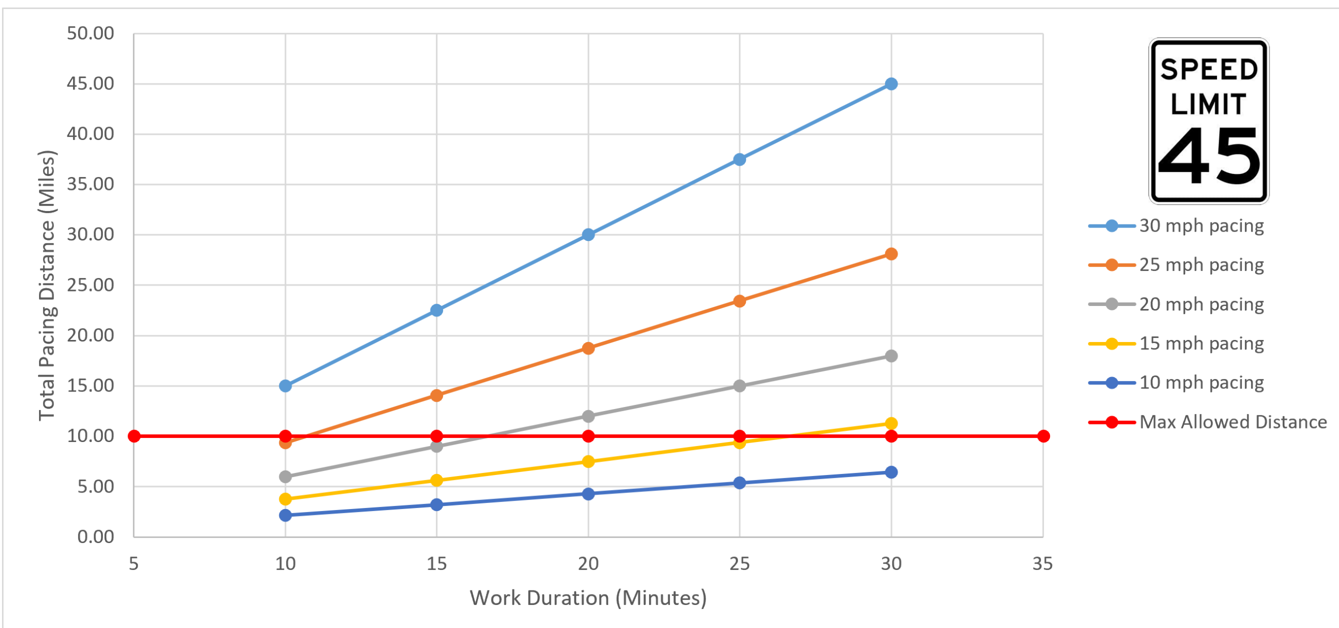

Figure B.6 Rolling slowdown ranges for 45 mph roads.

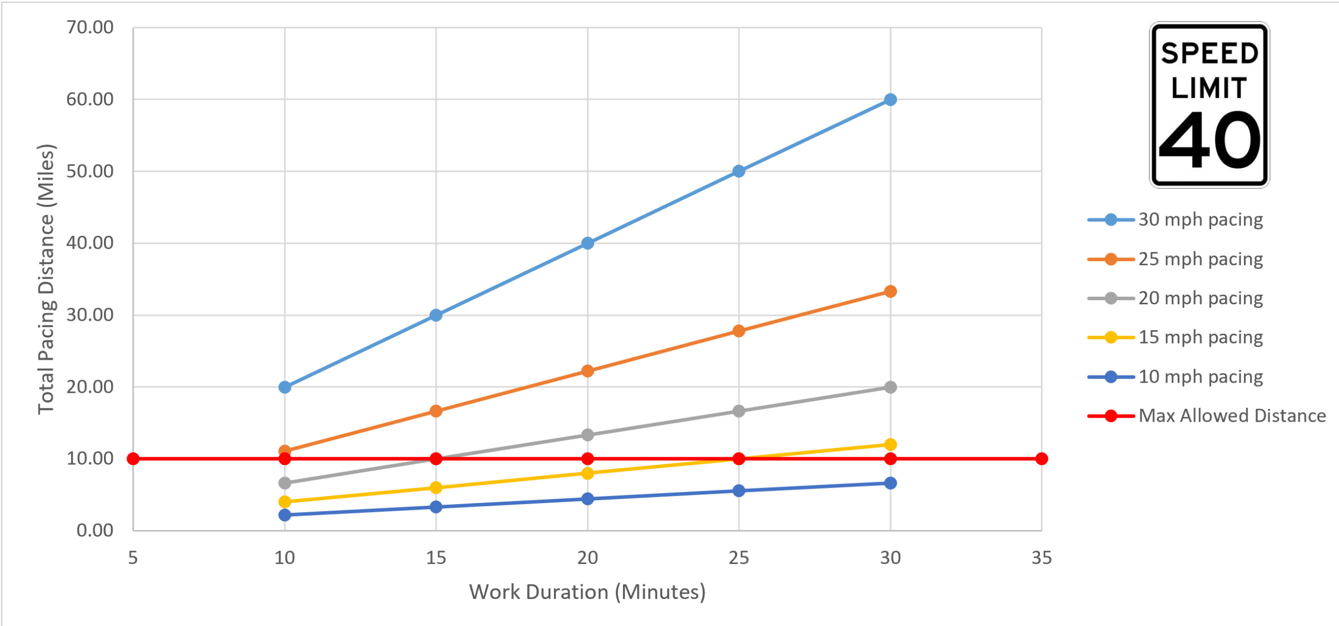

Figure B.7 Rolling slowdown ranges for 40 mph roads.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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