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Addressing Unpredictable Sources of Congestion

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16. Abstract - In this study, we assessed the state-of-the-practice methods of deploying incident management strategies and investigated areas for improvement. We also developed a framework for detecting secondary crashes on interstate corridors. Two case studies were conducted—the Alabama study focuses on assessing the state agency's service patrol deployment criteria and the North Carolina study mainly deals with the secondary crash detection framework. Concerning the framework for detecting secondary crashes, we chose another interstate corridor (I-40/85 between Greensboro and Durham) in North Carolina. The framework uses the spatiotemporal proximity of any two incidents. The study also reveals several channels of future research concerning unpredictable congestion mitigation. The choice of operational treatments (e.g., hard-shoulder running and variable speed limit) is important and needs further evaluation for different incident types. The accuracy of detecting secondary crashes depends on the overall crash rate, crash-reporting criteria, and geometry. For example, the proposed method may need to be adjusted for dense road networks where many roads run close and parallel to the corridor of interest. Police-reported crash descriptions can contain helpful information as well, but many public agencies are stepping back from releasing the reports for research purposes due to data privacy issues.

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EXECUTIVE SUMMARY

Incident management strategies for unpredictable congestion rely on information concerning the sources and impacts of those events. Their impacts, in addition to congested roadways, constitute disrupting freight-movements and occurrences of secondary crashes. In this study, we assessed the state-of-the-practice methods of deploying incident management strategies and investigated areas for improvement. We also developed a framework for detecting secondary crashes on interstate corridors. Two case studies were conducted—the Alabama study focuses on assessing the state agency's service patrol deployment criteria and the North Carolina study mainly deals with the secondary crash detection framework.

The Alabama Department of Transportation (DOT) currently uses an incident factor (IF) metric to determine service patrol needs. It accounts for the AADT and average crash rate of interstate corridors. We tested whether considerations of roadway geometry, day of the week, and freight movements would impact the current deployment decision based on IF's. Data from two interstate corridors (I-65 and I-565) showed that while non-recurring delays on urban segments show a pattern associated with weekdays and weekends, there is no clear pattern for rural segments. Travel time and delay cost add new dimensions to the currently-used metric—especially since the latter accounts for the impacts on freight movements.

Concerning the framework for detecting secondary crashes, we chose another interstate corridor (I-40/85 between Greensboro and Durham) in North Carolina. The framework uses the spatiotemporal proximity of any two incidents. Travel time data were fused to find queued segments to confirm if there was a causal relationship between two incidents. To demonstrate, two event databases were used separately. The Traveler Information Management System (TIMS) database had fifty potential primary-secondary incident pairs out of the 169 reported events in a six-month period. Another database, the archived crash data, showed a lower percentage of pairs—59 pairs were identified out of 328 crashes. The difference in the outcomes from the two databases is attributed to their reporting criteria—not all crashes are included in the incident database, and not all types of incidents are included in the crash database. Probe-based travel time data showed that the segments between crashes were fully or partially queued for 76% of pairs found in the TIMS database. The counterpart number for the crash database is 61%. Currently, this corridor is covered by NCDOT's Safety Patrol program—we found that ALDOT's IF-based metric justifies this deployment choice.

The study also reveals several channels of future research concerning unpredictable congestion mitigation. The choice of operational treatments (e.g., hard-shoulder running and variable speed limit) is important and needs further evaluation for different incident types. The accuracy of detecting secondary crashes depends on the overall crash rate, crash-reporting criteria, and geometry. For example, the proposed method may need to be adjusted for dense road networks where many roads run close and parallel to the corridor of interest. Police-reported crash descriptions can contain helpful information as well, but many public agencies are stepping back from releasing the reports for research purposes due to data privacy issues.

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1. Introduction

1.1 Background

Non-recurrent congestion is one of the main sources of unreliable travel times on roadways today, and is one of the main foci of current traffic management schemes in an effort to improve mobility *(1).* As expanding infrastructure becomes more challenging, research for operational enhancements has become more critical to address increasing traffic volumes and improve travel time reliability. The Transportation Systems Management and Operations (TSMO) schemes cover strategies that seek to enhance mobility through operational strategies rather than infrastructure expansion. Several of these strategies are targeted toward unpredictable and non-recurrent sources of congestion by proactively adapting to changing traffic conditions. They can be grouped into 14 categories, as shown in Table 1-1:

Table 1-1: TSMO Strategies

Work Zone Management	Traffic Incident Management
Special Event Management	Road Weather Management
Transit Management	Freight Management
Traffic Signal Coordination	Traveler Information
Ramp Management	Congestion Pricing
Active Transportation and Demand Management	Integrated Corridor Management
Improved Bicycle and Pedestrian Crossings	Connected and Automated Vehicle Deployment

Source: FHWA *(1). Transportation Systems Management and Operations (TSMO) Plans*. Federal Highway Administration, Washington, D.C., 2020. Available from: https://ops.fhwa.dot.gov/tsmo/#q1

Of these strategies, traffic incident management is of particular interest to researchers because traffic incidents (i.e., accidents and road breakdowns) are a common cause of non-recurrent congestion. These incidents account for nearly half of non-recurrent congestion and up to 25% of roadway congestion as a whole *(1)*. They may also degrade traffic operation and safety by causing further upstream crashes (also called secondary crashes). Popular strategies to manage traffic incidents include service patrol deployment, advanced traveler information deployment, traffic detours, and integrated corridor management *(2–6)*.

A major decision-making challenge associated with deploying any such strategy is where and when to deploy them. Intuitively, the most benefit from an incident management strategy may come from a location that experiences frequent incidents, given that other infrastructure needs to forge the plan can be easily met. In addition to frequency, the impact of incidents could be a performance metric. It can be quantified through the traffic demand level, the resulting congestion duration and queue length, and the likelihood of causing a secondary crash via shockwave propagations.

This research focuses on traffic operational and incident-related factors that are imperative to incident management strategies. We scrutinized the current practices concerning incident management strategies and chose a popular one to find scopes for improving the decision-making criteria. Specifically, we tested performance metrics involving incident frequency and impact and developed a method to detect secondary incidents caused by primary incidents.

1.1.1. Incident Frequency and Impact

In this report, the term incident refers to construction activities and crashes. Their frequency within a period has been used as an essential metric for travel time reliability analysis. Song et al. *(7)* and Ahmed et al. *(8)* combined the frequency, duration, and queue length of recurring congestion events to develop a single metric. The method could have been retrofitted to non-recurring incidents, but there is a threshold on the probability of a particular event type, which filters out all non-recurring events. The Alabama Department of Transportation (ALDOT) developed a metric *(2)* for detecting freeway segments that have high incident frequency and high traffic demand. However, the metric does not account for the variation of traffic demand and incident probability by time. Moreover, rural highways with high proportion of freight traffic might not get enough attention than what they need since the current method does not account for truck proportion exclusively.

In this study, we will examine the ALDOT method of detecting candidate locations for deploying incident management strategies. The technique will be applied to two case study sites to determine their need for incident management strategies. We will also test whether factors like road geometry, freight demand, and temporal variation of traffic demand and incident frequency need to be considered in the process.

1.1.2. Primary-secondary Incident Pairs

A secondary incident is one that happens as a result of a prior incident. According to the Federal Highway Administration, one in every five car crashes is a secondary incident. In the context of incident management deployment, they play an important role because the benefit-cost balance of the deployment could sway significantly depending on their occurrence rate. The change in the secondary incident rate before and after deploying an incident management strategy could be a performance metric. The secondary incident rate is likely correlated with the primary incident rate. Still, the secondary rate adds value as a separate metric since it can be reduced significantly by quickly deploying service patrols or other tactics for the primary incidents, even if the overall primary crash rate remains the same.

Despite their importance in safety and incident management research, it is hard to determine if there is any causal relationship between any two incidents. In this study, we developed a method to detect potential secondary incidents and the corresponding primary reason. From here onward, an incident pair with such a causal relationship is termed a potential primary-secondary pair. Unlike other studies on secondary incident detection, we considered both construction activities and crashes as the primary reason since our focus is on the overall incident management need for a site. In most cases, the secondary incidents are a crash, so the terms *secondary incident* and *secondary crash* are used interchangeably.

1.2 Objectives

In short, the objectives of this study can be listed below.

- To review the current practices adopted by different transportation agencies to manage unpredictable sources of congestion on freeways
- To develop frameworks to support the planning and monitoring of strategies that address unpredictable sources of congestion
    - To assess the current performance of an interstate corridor in terms of non-recurrent congestion using a state-of-the-practice method
    - To incorporate the impacts of congestion on freight movement into service patrol-need assessments
    - To develop and test a method for detecting potential primary-secondary incident pairs

1.3 Report Organization

The report is organized as follows. The next chapter presents a review of the literature on current practices adopted by public agencies to tackle non-recurrent congestion, with the main focus on incident management strategies. The following two chapters demonstrate two case studies—one on two interstate corridors in Alabama and the other involving one corridor in North Carolina. In the first case study, we tested the ALDOT method of prioritizing service patrol needs and investigated how it can be improved. The second case study mainly deals with the secondary crash detection technique. It also assesses the need for service patrol at the site using the ALDOT method. The final chapter summarizes the main findings and future research needs.

2. Literature Review

This literature review seeks to first identify and evaluate the primary sources of traffic congestion, and explore general impacts and guiding factors behind solutions to such sources. Then, it looks at the extent to which agencies within the Southeast have implemented TSMO strategies, specifically in response to non-recurrent congestion. In determining what strategies are being implemented, this review also explores the reported benefits and length of implementation of TSMO strategies on a state-by-state basis. Lastly, the review explores TSMO strategies implemented outside the Southeast region, including those within the United States and internationally. Furthermore, it looks at strategies proposed by the literature or being currently piloted to give a general overview of the state of non-recurrent congestion mitigation practices.

2.1 Sources of Non-Recurrent Congestion

The FHWA defines four primary sources of non-recurrent congestion: weather, traffic incidents, work zones, and special events. First, weather incidents, such as heavy rainfall, high winds, and snow, are an identified source of non-recurrent congestion. These impacts vary depending on the roadway and severity and type of roadway, but decreases in average speeds and traffic flows are observed for most weather events. Under light rain or snow, average speeds on freeways are reduced up to 13% and capacity is reduced up to 11%, and under heavier conditions, average speeds are reduced up to 40% and capacity is reduced up to 27% *(1)*. Similar effects are seen on signalized roads, where weather incidents resulted in decreased average speeds of up to 25% under moderate rain or snow, with an up to 50% decrease in average speeds under severe conditions as observed through multiple studies *(9)*. This non-recurrent congestion justly results in decreased travel time reliability, particularly under snowy conditions while dependent on preparation methods. Decreased travel time reliability is also exacerbated by higher traffic volumes, where greater variations in travel times are observed under adverse weather conditions during peak travel hours *(10)*.

Accidents and road breakdowns (collectively termed "traffic incidents") are a common cause of non-recurrent congestion on roadways. These incidents account for nearly half of non-recurrent congestion and up to 25% of roadway congestion as a whole *(1)*. Similar to weather incidents, the effect of traffic incidents is exacerbated under heavier traffic volumes, where decreased travel time reliability on freeways specifically has been observed for up to 90 minutes after the incident occurred. However, the same study also noted that smaller injury crashes caused little to no significant effect on travel times under smaller traffic volumes, while severe and/or fatal crashes were significant under nearly all traffic volumes observed. The location of lanes blocked due to the incident, most notably in the right lanes near on- or off-ramps, also played a key role in the variation of travel times *(11)*. TSMO strategies addressing traffic incidents are often grouped under the acronym Traffic Incident Management (TIM) strategies.

Work zones, usually resulting in lane or shoulder closures for construction, are another source of non-recurrent congestion. While these lane closures do reduce capacity of roadways, this decrease in travel time reliability is also due to the rapid accelerations and decelerations associated with most work zone traffic management schemes. Increased traffic volumes also decrease the reliability of travel times due to similar factors *(12)*. These lane closures in response to work zones do vary depending on the roadway and nature of construction, but current temporary traffic control elements around work zones are regulated in the Manual on Uniform Traffic Control Devices. This document gives current guidance on recommended taper and buffer spaces for most roadways.

Special events include the often irregular yet significant sources of non-recurrent congestion due to social activities, such as sporting events, fairs, and festivals. While any event may cause congestion, its effects are unpredictable and irregular, in a fashion that varies depending on the nature of such event. A study comparing congestion due to an NFL game versus congestion due to a NASCAR race noted multiple differences in the period of higher traffic volumes and their respective impacts on nearby roads. Drivers were more likely to arrive later to an NFL game, and decreases in travel time reliability were observed throughout the downtown location of the stadium. However, the rural location of the NASCAR race saw higher traffic volumes notably earlier to the start time of the event, yet the congestion was more localized between the speedway and nearby interstate *(13)*. Thus, the location of special events also plays a key role in its congestion, most significantly between rural and urban locations. In a separate study on rural West Virginia festivals, increases in travel times were observed at times that did not coincide with usual peak volumes on local roads. This congestion was exacerbated by unpredictable traffic volumes and local roads that were not designed for the volume and types of vehicles travelling to such events *(14)*.

2.2 Strategies Implemented in the Southeast

The review of TSMO strategies implemented in response to non-recurrent strategies in the Southeast focuses on six states: Alabama, Florida, Georgia, North Carolina, South Carolina, and Tennessee. **Table 2-1** organizes the comprehensive overview of implemented TSMO strategies by categories identified in **Table 1-1** and by state. While the table does focus on strategies used to mitigate non-recurrent congestion, many of these strategies are adaptable for recurrent congestion as well. Furthermore, some categories, such as Transit Management and Improved Bicycle and Pedestrian Crossings, represent TSMO strategies as part of a comprehensive overview of operation improvements implemented at the state level.

Table 2-1: TSMO Strategies by State

	Alabama	Florida		Georgia	North Carolina	South Carolina	Tennessee
	Work Zone Management						
Dynamic Lane Merging Systems	*n/a*	• Simplified dynamic late ("zipper") merge system (DLMS) *(pilot)* (15)		*n/a*	• Dynamic zipper merge (DZM) (16)	*n/a*	*n/a*
Variable Speed Limits (VSL)	*n/a*	Yes (17, 18)		Yes (18)	Yes (3)	Yes (19)	*n/a*
Smart Work Zone Technologies	• Portable/changeable message signs (PCMS) • Queue detection system (QDS) (20 21)	• Automated queue warning (AQW) • Motorist Awareness System (MAS) • Portable/changeable message signs (PCMS) (22, 23)	•	• Portable/changeable message signs (PCMS) (24)	• Portable/changeable message signs (PCMS) (25)	• Portable/changeable message signs (PCMS) (19)	• Portable/changeable message signs (PCMS) • "Protect the Queue" trucks (PTQ) • Signal retiming (26, 27, 28)
	Traffic Incident Management						
Incident Service Patrols	• Alabama Service and Assistance Patrol (ASAP) (29)	• Florida Road Rangers • Incentivized incident clearance programs (RISC) (3, 4)	•	• GDOT Highway Emergency Response Operators (HERO) (30, 31)	• NCDOT State Farm Safety Patrol (32)	• SCDOT State Highway Emergency Program (SHEP) (33)	• TDOT HELP Service Patrols (34)
Additional Strategies	*n/a*	• Data collection (SunGuide software) (4)	•	• Coordinated Highway Assistance & Maintenance Program (CHAMP) (5, 6)	• Traffic Incident Management Training Track (35)	• Data collection (CCTV, traffic detection systems) (19)	• Traffic Incident Management Training Facility (36)
	Special Event Management						
Case Studies	-	<u>Daytona Beach</u>: • Data collection (CCTV) • DMS & PCMS systems • Traffic signal retiming (37)		<u>Superbowl LII</u>: • All-way pedestrian crossings • Data collection (CCTV) • Traffic signal retiming (38)	-	-	-
	Road Weather Management						
Weather Detection Systems	• Fog detection (low-visibility) & warning system (39)	• High-wind sensor & alert system (with TMC's) • Motorist Warning System	•	• Automated Adverse Visibility Warning and Control System (AVWCS) (41)	• Flood Inundation Mapping & Alert Network for	• Fog detection (low-visibility) & warning system (39)	• Fog detection (low-visibility) & warning system • Road Weather Information System (RWIS)

	Alabama	Florida		Georgia	North Carolina	South Carolina	Tennessee
		(MWS) for wet pavement (39, 40)		• Road Weather Information System (RWIS) (40, 41)	Transportation (FINMAN-T) (42)		(38, 43)
Active Traffic Management	• Variable speed limits (VSL) (39)	• Strategic road closures • Variable speed limits (VSL) (44)	•	• Variable speed limits (VSL) (45)	• Weather-related signal timing (40)	• Variable speed limits (VSL) (44)	• Variable speed limits (VSL) (18)
Disaster Response Strategies	Hurricanes: • Lane reversal on major arterials • Road detours & evacuation routes (46)	Hurricanes: • Alternate/redundant traffic management centers (TMC's) • Emergency shoulder use (ESU) • Road detours & evacuation routes (47, 48)		*n/a*	Hurricanes: • Active traffic management (with TMC's) • Lane reversal on major arterials • Road detours & evacuation routes (49)	Hurricanes: • Lane reversal on major arterials • Road detours & evacuation routes (39)	*n/a*
	Transit Management						
Demand-Response Transit Application	*n/a*	• NeighborLink flex service (50, 51)		*n/a*	*n/a*	*n/a*	*n/a*
Mobile Ticketing and Payment	• Mobile Proximity Fare Collection Tool (MPFCT) *(pilot)* (52)	• Contactless payment (Miami Metrorail, LYNX PawPass) (51, 53, 54)	•	• Contactless payment (Breeze Mobile, Xpress) (55, 56)	• Contactless payment (TouchPass) (57)	*n/a*	*n/a*
	Freight Management						
ITS Technology Implementation	• Weigh-in motion (WIM) equipment (58, 59)	• Truck Parking Availability System (TPAS) • Weigh-in motion (WIM) equipment (60, 61)	•	• Weigh-in motion (WIM) equipment (62)	• Weigh-in motion (WIM) equipment (63)	• Weigh-in motion (WIM) equipment (64)	• TDOT SmartPark *(pilot)* • Weigh-in motion (WIM) equipment (65)
	Traffic Signal Coordination						
Advanced Signal Control	• Adaptive signal control technology (ASCT) (66, 67)	• Adaptive signal control technology (ASCT) (68)	•	• Adaptive signal control technology (ASCT) (69)	• Adaptive signal control technology (ASCT) • Statewide central signal system (70)	• Adaptive signal control technology (ASCT) (71)	• Adaptive signal control technology (ASCT) (72)
	Traveler Information						
Web / Mobile Application	• ALGO Traffic web application for real-time traffic information (73)	• FL Advanced Traveler Information System (FLATIS) / FL511 app for	•	• PeachPass GO! for tolls & traffic advisories	• DriveNC.gov web application with real-time traffic advisories (77)	• 511 SC Traffic app for general traffic information (78)	• SmartWay web application for real-time traffic information (79)

	Alabama	Florida		Georgia	North Carolina	South Carolina	Tennessee
		general traffic information (4, 74)		• Georgia 511 App with general traffic (75, 76)			
511 Number	*n/a*	Operated by FDOT (74)		Operated by GDOT (76)	Operated by NCDOT (80)	Operated by SCDOT (78)	Operated by TDOT (81)
Dynamic Messaging Systems	Yes	Yes		Yes	Yes	Yes	Yes
	Ramp Management						
Ramp Metering	*n/a*	• Interstates & major state routes (82)	•	• Most Metro Atlanta Interstates (83)	• Introduced on some Interstates (84)	*n/a*	*n/a*
	Congestion Pricing						
Variable Tolls / Express Lanes	*n/a*	• I-95 Express Lanes utilize variable pricing (85)	•	• I-75 & I-85 Express Lanes utilize variable pricing (86)	• I-77 Express Lanes utilize variable pricing (87)	*n/a*	*n/a*
	Active Transportation and Demand Management						
Traffic Management Centers (TMC's)	Yes	Yes		Yes	Yes	Yes	Yes
	Integrated Corridor Management						
Case Strategies	• Improved data collection using ALGO Traffic to target high-volume corridors (88)	• STAMP Action Plan prioritizes corridor integration, updated standards, & increased traffic signal communication (89)	•	• Current ITS plan focuses on corridor-wide signaling & traffic management improvements (90)	• Piloted Bluetooth technology & ICM implementation on Interstates (70)	• Corridor operational improvements include access management, signal timing, & DMS systems (91)	• Current TSMO plan identifies primary corridors for comprehensive technologies (92, 93)
	Improved Bicycle and Pedestrian Crossings						
Pedestrian Detection Systems	*n/a*	• LiDAR passive pedestrian detection system *(pilot)* • Signal timing using pedestrian detection data (94, 95)	•	• Mobile Pedestrian Signal System (PED-SIG) *(pilot)* (90)	*n/a*	*n/a*	*n/a*
	Connected and Automated Vehicle Deployment						
CAV Testing Facility	*n/a*	• SunTrax testing facility (4)		*n/a*	*n/a*	*n/a*	• CAV Tech. Evaluation Center (CAVTEC) (96)
Comm. Infrastructure	• DSRC radio installations for data collection (88)	• I-75 FRAME roadside units	•	• Emergency vehicle signal preemption (98)	• DSRC radio installations for data collection	*n/a*	• DSRC radio installations for data collection

	Alabama	**Florida**		**Georgia**	**North Carolina**	**South Carolina**	**Tennessee**
		• THEA DSRC & RSU deployment (94, 97)					
Traffic Signal Infrastructure	• Signal Phase and Timing (SPaT) (88)	• Signal Phase and Timing (SPaT) (99)	•	• Signal Phase and Timing (SPaT) (100)	• Signal Phase and Timing (SPaT)	*n/a*	• Signal Phase and Timing (SPaT)

This overview of Southeastern strategies presents some notable similarities among state agencies. With regards to mitigating non-recurrent congestion at work zones, all states have adopted driver communication systems including dynamic messaging and portable changeable messaging devices. Furthermore, nearly all states have developed an incident service patrol system, generally referring to a fleet of dedicated, mobile units tasked with responding to accidents, stalled vehicles, or mechanical breakdowns with the goal of quickly clearing travel lanes and returning to normal traffic flow. Research has shown that these programs are highly effective under most traffic volumes, such as in an evaluation of the Florida Road Rangers that found them influential in improving travel time reliability due to accidents on Florida freeways *(101)*. Note that the Alabama Service and Assistance Patrol (ASAP) for incident management is discussed in detail in Chapter 4 of this report. The majority of these states, too, have also implemented improved data collection and incident preparation systems to reduce the effects of traffic incidents.

Outside of the primary sources of non-recurrent congestion, **Table 2-2** also demonstrates commonalities among further TSMO strategies, even those that are more inclined towards recurrent congestion. Most states have implemented a 511-traffic number and/or migrated such information to a web or mobile application, such as South Carolina's dedicated 511 number operated by SCDOT and its similarly named traffic application for traveler information. Despite having varying levels of urbanization, many states have begun exploring mobile payment and improved mobile applications for transit use, and all Southeastern states studied have adopted freight weigh-in-motion equipment, for instance, to improve speeds and reliability for such travel.

The implementation of other technologies, though, is more sporadic among Southeastern agencies. Few have piloted some work zone improvement technologies, including queue warning systems or dynamic lane merging, that have only been explored primarily in Florida and North Carolina. On the other hand, agencies' response to weather differs primarily due to varying needs among states in different climates. While Florida has adopted stronger hurricane response practices and developed long-term high-wind warning systems, Tennessee has adopted low-visibility warning systems as a contrast due to its largely different location. States' implementation of ramp metering and variable pricing (express lanes) is even more sporadic, with that being limited to three states with greater urban centers. These contrasts do represent the variability and adaptability of many TSMO strategies, in that their implementation is largely influenced by need and organization ability of agencies to research, develop, and implement such practices.

Table 2-2 adds additional information regarding the length of implementation of these strategies at the state level, with each strategy's tenure being presented up to or greater than five years. This overview gives insight into the maturity of TSMO strategies and their effectiveness at the state level, with their time in operation being used as a more general indication of their development and usefulness to each respective agency. For this review's purposes, five years or more is viewed relatively similarly as an indication that the TSMO strategy has been proven and is effective in operational improvements. Furthermore, the table also adopts the distinction *"pilot"* for strategies that have been implemented in a small-scale environment and lack standard usage for mitigating non-recurrent congestion. While not standard strategies, these pilots are representative of the direction agencies are taking in adopting newer, technologically advanced practices.

Table 2-2: Length of Implementation of TSMO Strategies

	Alabama	Florida	Georgia	North Carolina	South Carolina	Tennessee
Work Zone Management	• QDS: 2 yrs • PCMS: >5 yrs	• DLMS: >5 yrs • VSL: >5 yrs • AQW: 3 yrs • MAS: >5 yrs • PCMS: >5 yrs	• VSL: >5 yrs • PCMS: >5 yrs	• DZM: 2 yrs • VSL: >5 yrs • PCMS: >5 yrs	• VSL: >5 yrs • PCMS: >5 yrs	• PCMS: >5 yrs • PTQ trucks: >5 yrs • Signal timing: 2 yrs
Traffic Incident Management	• ASAP: >5 yrs	• Road Rangers: >5 yrs • RISC: >5 yrs • SunGuide: >5 yrs	• HERO Units: >5 yrs • CHAMP: 4 yrs	• State Farm Patrol: >5 yrs • TIM Track: 3 yrs	• SHEP: >5 yrs • Data collection: >5 yrs	• HELP: >5 yrs • TIM Facility: >5 yrs
Special Event Management	-	-	-	-	-	-
Road Weather Management	• Fog detection: >5 yrs • VSL: >5 yrs	• Wind alert: >5 yrs • Road closures: >5 yrs • VSL: >5 yrs	• AVWCS: >5 yrs • RWIS: >5 yrs • VSL: >5 yrs	• FINMAN-T: 2 yrs • Signal timing: >5 yrs	• Fog detection: >5 yrs • VSL: >5 yrs	• Fog detection: >5 yrs • RWIS: >5 yrs • VSL: >5 yrs
Transit Management	• MPFCT: 3 yrs	• NeighborLink: 4 yrs • Contactless: 4 yrs	• Contactless: 4 yrs	• Contactless: 2 yrs	*n/a*	*n/a*
Freight Management	• WIM: >5 yrs	• TPAS: 3 yrs • WIM: >5 yrs	• WIM: >5 yrs	• WIM: >5 yrs	• WIM: >5 yrs	• SmartPark: >5 yrs • WIM: >5 yrs
Traffic Signal Coordination	• ASCT: >5 yrs	• ASCT: >5 yrs	• ASCT: >5 yrs	• ASCT: 4 yrs • Central signaling: 3 yrs	• ASCT: >5 yrs	• ASCT: >5 yrs
Traveler Information	• ALGO Traffic: >5 yrs • DMS: >5 yrs	• FL511 (app): >5 yrs • 511 (#): >5 yrs • DMS: >5 yrs	• PeachPass GO!: >5 yrs • GA 511: >5 yrs • DMS: >5 yrs	• DriveNC.gov: >5 yrs • 511: >5 yrs • DMS: >5 yrs	• 511 (app): >5 yrs • 511 (#): >5 yrs • DMS: >5 yrs	• SmartWay: >5 yrs • 511: >5 yrs • DMS: >5 yrs
Ramp Management	*n/a*	• Ramp meters: >5 yrs	• Ramp meters: >5 yrs	• Ramp meters: 4 yrs	*n/a*	*n/a*
Congestion Pricing	*n/a*	• I-95: 2 yrs	• I-75: 4 yrs • I-85: >5 yrs	• I-77: 2 yrs	*n/a*	*n/a*
Active Transportation and Demand Management	• TMC's: 4 yrs	• TMC’s: >5 yrs	• TMC’s: >5 yrs	• TMC’s: >5 yrs	• TMC’s: >5 yrs	• TMC’s: >5 yrs
Integrated Corridor Management	-	-	-	-	-	-
Improved Bicycle and Pedestrian Crossings	*n/a*	• LiDAR: 2 yrs • Signal timing: 4 yrs	• PED-SIG: 2 yrs	*n/a*	*n/a*	*n/a*
Connected and Automated Vehicle Deployment	• DSRC: 4 yrs • SPaT: 4 yrs	• SunTrax: <1 yr • I-75 FRAME: <1 yr • THEA: 1 yr • SPaT: 2 yrs	• Signal preemption: 3 yrs • SPaT: 2 yrs	• DSRC: • SPaT:	*n/a*	• CAVTEC: • DSRC: • SPaT:

For the most part, the table indicates that the majority of operational practices implemented by state agencies have been used for more than five years. As an example, the practice of incident service patrols has been implemented by all states for significantly longer than five years, and even ramp meters have been implemented as far back as the 1996 Olympic Games in Atlanta. Variable speed limits, a common TSMO strategy that can be utilized in response to a variety of non-recurrent congestion sources, are also mature in their adoption among Southeastern states. However, the more recent TSMO strategies have revolved around connected vehicle technology or emerging research into other operational practices. For instance, North Carolina's pilot of an enforced dynamic "zipper" merge around work zones was brought on by new sensor technology and is still limited in its implementation along major Interstates *(16)*. Connected vehicle technologies, too, have been explored by all but one (South Carolina) Southeastern agency for use in operational enhancement, but many are still in their infancy in their Southeastern deployment. Georgia's connected vehicle deployment, for instance, has involved pilots within the past couple years by more local agencies, including Gwinnett County's emergency vehicle preemption system or Atlanta's Smart Corridor project. Both represent the relative newness of much of connected vehicle technology to the majority of non-recurrent traffic management in the Southeast.

In general, then, most Southeastern states have continued with proven strategies, and any recent adoption of new strategies has been primarily around emerging technologies or brought on by increasing difficulties of standard solutions to traffic congestions. With regards to non-recurrent traffic congestion in particular, though, TSMO strategies have more or less been well-established for the majority of studied agencies. However, some agencies have begun exploring technologies more recently, notably those discussed previously from **Table 2-1**. Their length of implementation, usually of less than two years, reflects these newer operational strategies being tested and deployed among more progressive agencies, such as in Georgia and Florida. These states similarly have larger urban centers, and as discussed previously, are obviously more adaptable and resource-able to adopt newer TSMO strategies.

2.3 Strategies Proposed by Literature

A review of proposed strategies to mitigating non-recurrent congestion does bring up some further strategies not widely implemented by transportation agencies, especially those in the Southeast. While these have yet to be proven outside of limited testing, they do present potential solutions to traffic congestion caused by non-recurrent sources. Furthermore, in several cases, the literature also presents the hindrances and obstacles to deploying these newer strategies on a larger scale. Such limitations are important to note as representative of obstacles individual agencies may face moving forward with implementing more novel strategies.

Work zone queues, for instance, have been the subject of some recent research into mitigation strategies even beyond more connected vehicle technologies. For instance, a dynamic lane merging method dubbed the "New England merge" studied a scheme of managed merging closer to the taper point of the work zone, and was found effective in reducing non-recurrent congestion and increasing safety on two-lane highways. This merging strategy is similar to those mentioned in **Table 2-1**, The study did note, though, that there may be some ethical questions around cooperative driving schemes and the extent of enforcement of merging policies around work zones *(12)*.

Still, the continuance of research into connected vehicles shows promising signs in reducing non-recurrent congestion around work zones. In simulations, the increased presence of connected vehicles has resulted in improved travel time reliability for drivers around work zones, particularly under higher traffic volumes. Including mean travel time and average travel speeds through work zones, a "critical market penetration" of connected vehicles was modeled to improve such measures by up to 40% *(102)*. These technologies, too, have been proven empirically to be feasible and applicable in accurately depicting travel times through work zones. Tested on a two-lane road in Minnesota, a portable DRSC-based communication system correctly predicted and broadcast the start of congestion and estimated travel times through work zone-caused congestion *(103)*. And, in Missouri, dynamic messaging signs and other ITS technologies have been implemented in successfully relaying information to drivers ahead of work zones. This information has benefitted both safety and traffic delay around work zones *(104)*. Such technology presents the future of connected vehicle adoptions on a more widespread scale.

2.4 Strategies Implemented Internationally

Outside of the United States, the implementation of novel operational strategies internationally presents a primary focus on connected and automated vehicle technology. In Europe, a consolidated EU initiative entitled the Knowledge Base on CAD (Connected and Automated Driving) lists nearly 300 initiatives across the continent into emerging connected vehicle technologies *(105)*. Many of these are of specific interest to addressing non-recurrent congestion specifically. In the Netherlands, the Talking Traffic partnership has deployed traffic light data connected to in-car navigation and smartphone apps. This project seeks to further expand this program to provide real-time travel information based on variable speed limits and congestion along the driver's route *(106)*. Another consortium, Socrates 2.0, has sought to optimize traffic flow through widespread deployment of roadside in-car units throughout Europe, with a goal of coordinating traffic management across the continent. The group also promotes the implementation of these technologies as a primary step in preparing Europe for the advent of fully automated vehicles *(107)*. Lastly, the MAVEN project has developed infrastructure for more effectively implementing vehicle platooning utilizing adaptive, coordinated traffic light optimization and communication technologies. These include developing standards for V2I and V2V communications for European drivers and testing these methods for drivers *(108)*.

While these strategies are not entirely foreign to the United States and even the Southeastern region, they are more developed and wholly implemented. Therefore, these projects could be useful as a guide in the best operational and organizational methods of implementing TSMO strategies in response to non-recurrent congestion. And, for those strategies that are more useful for American projects, it would be useful to investigate the challenges and benefits of specific projects for implementation in the Southeast.

2.5 State Practice for Safety Patrol Deployment

The use of freeway service patrols is one method used by several states to support their incident management efforts. This strategy is discussed in detail since it is directly related to one of the case studies presented in this report. In addition to the southeast states, the notable strategies adopted by other states are also included.

2.5.1. Priority-Ranking and Expanding Freeway Service Patrols – North Carolina

As the state's population grew, and the urban areas in North Carolina experienced relative high traffic volumes and congestion, there arose the need to find an accurate, systematic method to identify the potential road segments that will receive highest deployment priority of freeway service patrols (FSP). Thus, the North Carolina Department of Transportation (NCDOT) with assistance from the FHWA Highway Safety Information System developed a decision support tool that allows easy planning and operational assessment of road segments. This was accomplished by comparing performance values between these segments, modeling the effect of using Freeway Service Patrols and estimating the key potential benefits of having the FSPs.

The NCDOT provided crash data with location information while the Highway Safety Information System (HSIS) database provided the facility information such as the annual average daily traffic and number of lanes. The crash data were used to check the occurrence of incidents on freeway facilities and pick out expansion criteria. According to Khattak et al., three index statistics were used to capture safety and congestion for each of the segments checked, namely crashes per 100 million vehicle-mi, crashes per mile per year and AADT per lane *(109)*, The research developed a decision support tool that allows users to easily access delays, and evaluate existing or future FSP deployment. The tool provides (a) a statewide ranking for planning-level analysis, (b) single incident assessment to examine the incident effects without the presence of an FSP and (c) operational level of analysis to determine the annual benefits of implementing an FSP based on the annual number of crashes entered by the user. The decision support tool requests as inputs the values of length of road segment, AADT, and the total number of annual crashes of the desired stretch of roadway. The cost of implementing an FSP is then calculated with the tool based on anticipated number of operating hours, cost of operating a vehicle for one hour and the total number of patrol vehicles necessary for covering the needs of existing facilities. Using the regression equation calibrated with the North Carolina FSP data, the decision tool is also able to predict the number of vehicles necessary for new facilities *(110)*. The vehicle estimation results, operating hours and costs are determined and benefit-cost analysis is performed to determine the most beneficial options for FSPs deployment. The research concluded that the FSP benefits would be higher if fuel and air quality savings were included in the calculations *(111)*. They researchers further recommended that a more thorough analysis of the effects of FSPs be conducted for FSP operating hours, segment lengths covered by the patrol teams, number of patrol vehicles, peak and nonpeak incidents and different roadway geometries.

2.5.2. Road Rangers – Florida

The Florida Department of Transportation has a contract with the Road Rangers whose job includes motorist assistance, temporary traffic control and incident management. The Road Rangers help mitigate the impacts of incidents on roadways by training and equipping their staff on vehicle disablements, handling roadway debris and traffic control set up at crash scenes. Construction presence, air quality monitoring, traffic volume, volume-to-capacity ratio, crash frequency and available shoulder width are all considered in decision making to establish routes for the Road Rangers. According to the Florida Department of Transportation (FDOT), the Road Rangers program was set up in 2013 and provided 374,971 assists that year and more than 4.3 million assists since then *(112)*. A 2010 study funded by the FDOT showed that the benefit-cost ratio of the Road Ranger program was 6.68:1 as quoted by *Lin et al. (113)*. The quest for provision of a decision support system for FDOT staff came because of the difficulty in reaching a consensus on whether a roadway needs the services of a safety service patrol (SSP). This led to the identification of the critical factors that are important for deployment decisions on service patrols such as traffic volume, number of crashes, available funding, and design attributes of the roadway segments. To check these critical factors with the planning guidelines of the SSP, a cross tabulation was performed using national survey results. These survey results were weighted differently from the most important to the least important.

Five years' worth of data of traffic crashes (from 2011 to 2015) on Florida freeways were used to evaluate the crash-critical factors as the crashes were normalized to AADT and number of lanes, and employed in the computation of the number of incidents using the negative binomial regression model. The results from the model computation showed segment length and AADT having positive coefficients, which indicated that increased exposure yielded increased incidents *(112).* Furthermore, Carrick et al. reported that a negative coefficient was observed with respect to the number of lanes, meaning that an increase in the number of lanes resulted in fewer incidents per lanes, assuming all other factors were constant *(114)*. An increase in portion of trucks increased the predicted number of incidents for two models but decreased incidents in the other two. Also, Carrick et al. noted that segments that had neither end as an interchange had fewer total incidents than those that had one or both ends as interchanges *(114)*. A user friendly and practice ready spreadsheet program was created to collect user input, perform calculations, apply decision logic, and render a recommendation to enable the decision-making process of deploying SSPs in an easy and effective manner.

2.5.3. Safety Service Patrol – Oregon

The Oregon Department of Transportation (ODOT) put up a warrant process to deploy Safety Service Patrol (SSP) in the state. As stated by Wood, the thought behind the warrant process is the link between the crash frequency and traffic volumes *(115)*. Wood summarized the seven warrants developed by ODOT as incidents reach acute levels when the Annual Daily Traffic (ADT) gets close to 75,000 vehicles per day causing rise in delay to motorists. The safety service patrol teams that assuage these incidents are deployed using the warrants shown as follows *(115)*:

1. Construction, Holiday, and Special Event. Construction, holidays, and special events were considered as short-term incidents as they reduce capacity or cause peaks in traffic volume.
2. Air Quality Conformity/Transportation System Management. Metropolitan Planning Organizations often identify SSPs as a method of achieving air quality attainment goals in the urban areas.
3. Critical Infrastructure (includes bottleneck locations). Areas of a freeway like bridges, tunnels and interchanges are critical to the efficient flow of traffic in a region.
4. ADT greater than 75,000. Freeway volume is directly correlated to the incident frequency. A critical threshold is reached at around 75,000 ADT.
5. Volume-to-Capacity Ratio greater than 1. The warrant suggests that the presence of recurring congestion can mandate the use of Safety Service Patrols.
6. Crash Frequency greater than 200. A 2-mile segment of freeway with 3-year crash history of 200 or more crashes warrants the need for SSP.
7. Shoulder Width less than 6 feet. Sections of the roadway with insufficient shoulder widths offer no space for vehicular breakdowns or debris. This reduces the capacity when an incident occurs thereby creating a safety hazard.

ODOT suggests that it is permissive to deploy SSPs if a single warrant is met, leaving the implementation decision to the discretion of the management. However, if warrants 4 and 5 or warrant 6 are meet, deployment of SSP is recommended because of the certainty that the affected section of freeway has deficiencies in its operation.

2.5.4. Freeway Service Patrol – California

The California Department of Transportation (Caltrans) with assistance from researchers at the University of California-Berkeley created a Freeway Service Patrol Evaluation (FSPE) model. Skabardonis and Mauch stated that the FSPE model calculates a benefit-cost ratio for the Freeway Service Patrol beats or routes based on the cost of the FSP service on a beat and reductions in delay of motorists, fuel consumptions, emissions that are attributed to the FSP operations *(116)*. They also reported that the FSPE model predicts the cost-effectiveness of providing FSP service on freeway sections without FSP service. The model is able to tell the total number of FSP assists based on the traffic characteristics, the geometry and the service patrol’s hours of operation, after which it calls on the model to guesstimate the route as if the FSP assists were known *(117)*.

2.5.5. Safety Service Patrol – Virginia

A Safety Service Patrol program was developed for the Virginia Department of Transportation (VDOT) to respond to local needs in different areas. While the need for SSP arose, the Virginia DOT’s Maintenance Program Leadership Group Report (MPLG) and the Statewide Incident Management Committee (SIM) were challenged to identify solutions to traffic problems resulting from incidents on Virginia's interstate roadways. A methodology often referred to as the MPLG methodology was developed in 1996 based on the criteria listed below *(118):*

1. Level of Service – a measure of traffic performance on the freeway segment.
2. Incident history- the number of incidents in the prior 3 years.
3. Planned projects- VDOT uses dollar value of projects in 6- year improvement program to check for safety implications of work zones.
4. Air quality- Using the binary variable of yes/no to decree attainment and non-attainment areas.
5. Access distance- The maximum distance an emergency vehicle must travel from an interchange to assist an incident that occur on the segment.
6. Length of structure- Structures that are long such as bridge or tunnel usually have reduced shoulder widths, hence making it unsafe for the motorist involved with breakdown vehicles to get assistance.
7. Annual Average Daily Traffic – to give information on the number of customers served by an SSP patrol.
8. Daily truck volume- indicating the number of trucks traveling the segment in 1 day.

The VDOT's SSP program falls in line with the incident detection/verification and response which are the cores of incident management. The program's mission is to provide initial response and promote and enhance the goals of incident management by patrolling the Commonwealth's interstate system and providing customer service related assistance for the safe and efficient transportation of motorist, goods and services in support of the economic, environmental and public demands placed on the system *(119, 120)*. The SSP placed priority on incidents on the travel portion of the highway, over incidents on the shoulder area and incidents in the rest areas, in that order. However, these priorities may differ due to the type of incidents such as HAZMAT spills and personal injury *(119, 121)*. According to VDOT and Landis et al., VDOT SSP staff were interviewed to gather information on the core set of functions for the VDOT's rural and urban SSP programs *(120, 122)*. The following information was obtained from these interviews:

1. Scene Management: To let the state police know about abandoned cars; provide cellular service to disabled motorists; provide directions and the state map of Virginia if requested by motorists; provide basic first aid and CPR if needed; communicate activities with State Traffic Centers and provide information to other responders; initiate maintenance action reports for any state property damage as a result of the incidents.
2. Traffic Management: To assist in controlling traffic at incident scenes; manage lane closures; verify, and manage operation of ramp-metering gates or High Occupancy Vehicle (HOV) gates in the urban areas.
3. Incident Clearance: To help jump start vehicles, provide gas, change tires, and provide air; remove debris; push vehicles to the shoulder; perform some minor mechanical repairs.

There were some limitations in the development of the VDOT SSP deployment planning tool. These limitations prevent its appositeness to statewide deployment decisions for the SSP, and include:

1. Limited data and inadequate model specification for incident history
2. Limited data for deriving the threshold score
3. Outdated threshold score
4. The methodology provides a binary answer for patrol deployment on a freeway section without paying attention to the time of day.
5. The criteria also seemed to be suited to urban areas than rural areas with greater point values for LOS and incident history.

After these limitations were identified, data related to all the routes were obtained. Traffic related data such as AADTs, lengths of sections, traffic flow profiles, percentage of trucks were all obtained from VDOT's traffic monitoring systems database. Data on the road geometry such as number of lanes, availability of left and/or right shoulders, and presence of high occupancy vehicle lanes were obtained from the VDOT's GIS online server. To obtain enough data for the estimation of the regression model used for the analysis, the *(117)* noted that the segments defined by the Traffic Management Systems website for each SSP route were used as independent observers. Washington et al. explained that Poisson and negative binomial (NB) regression are two major methods used extensively for traffic safety research *(123)*. Initially considered in the development of this SSP model, was the use of the Poisson model but the deviance and Pearson chi-square values obtained were higher than 1.0 indicating that the data were over-dispersed. Over dispersion indicates that the variance is greater than the mean and hence the assumption of a Poisson distribution is invalid, as in Poisson distributions, the mean is equal to the variance *(117)*. To take care of the over dispersion, Washington et al. recommended the use of negative binomial model for this study *(123)*. final regression equation obtained using the NB model showed that the coefficient of the percentage of trucks variable is negative. This implies that as the percentage of trucks increases, the number of incidents decreases. However, caution must be applied as the rural segments had lower incidents, higher truck percentages, lower AADTs, and lower average daily percent of ADT served. The MPLG study indicated some modifications as they derived additional segment-based decision variables. The study was then modified by using the incident history to replace the annual incidents per mile. Level of service, air quality, maximum access distance, maximum structure length, AADT, and daily truck volume remained the same. The complete planning tool was programmed into Microsoft Excel using a Visual Basic macro. This was developed to provide VDOT SSP with an easy-to-use mechanism to rank potential SSP routes.

The limitations of the planning tool are highlighted below *(117)*:

1. The shoulder widths, which affect incident occurrence, were not specified in the model as inconsistencies were found in the data sources. Some of the freeway segments had

both left and right shoulders, and the binary descriptors for the presence of shoulders were not included in the planning model.

2. Only one year's worth of incident data was analyzed because of the short timeline of the project. It is often advised that incident data in the prior 3 to 4 years be used to build the regression model.
3. The evaluation scale and weights for the segment-based variables were adopted from the MPLG study. There were claims that the weights applied to the variables were based on the MPLG committee's recommendations and are subjective in nature.
4. It was not possible to test the validity of the model in the study because all available incident data captured by VDOT's SSPs were utilized for the development of the incident planning model.

The study recommended that the decision-makers of the Safety Service Patrol team should prioritize the core functions of their programs in relation to the direct, indirect, and incidental benefits each provides, with emphasis placed on the functions that provide the most direct benefits *(117)*. It was also recommended that a statewide consistency with SSP core functions be maintained, and that each regional SSP manager should communicate and keep abreast of changes in core function priorities in other operations regions. The recommendation accented that the SSP deployment planning tool be used by VDOT's regional operations directors when considering the deployment of new patrols or altering existing ones. To achieve this, all existing and potential patrol routes need to be included in the evaluation. For future studies, it was recommended also that the directors of the VDOT regional operations should consider additional research that expands upon the current dataset.

2.5.6. The Hoosier Helper Program – Northwest Indiana

The Hoosier Helper program which is supported by the Indiana Department of Transportation (INDOT) roves about the 16-miles stretch of the six-lane Interstate 80-94 freeway commonly known as the Borman Expressway. The program also covers some other stretches of major highways in the state seeking and responding to incidents. The program, provides support at crash sites, supplies fuel, changing flat tires and calling private tow truck operators for motorists that need assistance. A simulation model was developed to carter for the freeway service patrols in the northwestern part of Indiana. The effort was driven by the need to tackle the issues of reliability of an emergency response system, facility location problem and to evaluate the effectiveness of a freeway service patrol program. Thus, the simulation model was created to estimate the effectiveness of the service patrol program for a wide range of parameters. The model according to *Pal and Sinha (124)* was created in four phases that covered the replication of the incidence occurrence, the traffic flow in different links at different times, the response vehicle movement in their respective patrol areas and the clearance of the incident *(124)*. Because the number of incidents occurring per day is a non-negative integer, Poisson distribution was used. Poisson distribution is a count distribution suitable for random variables with non-negative integers as outcome as predicted by *(125)*. Also, the nonhomogeneous Poisson distribution was used to model the incident generation as the rate of incident occurrence varied with time of day. The seasons, weekdays and weekends were incorporated into the model. Longitudinal location of incidents on various segments were assumed to be uniformly distributed along the entire link length while the lateral position of the incident with respect to shoulder presence or on lane was determined using probability distribution *(125)*. As the program patrolmen recorded the information regarding the incident, INDOT collected this information and used it to obtain the distribution of incidents by time of year and type of incident. The Poisson distribution was employed in calculating the number of incidents occurring in each hour as it generated nonnegative integers. The incident generation model was validated with the chi square test by juxtaposing the simulated and observed incidents. The two sets of data – simulated and observed, had similar confidence level values and critical values with little differences during certain hours of day. It was observed that the simulated speed was higher than the observed speed at night with the opposite happening during the day especially at the peak periods. This disparity according to Pal and Sinha is as a result of different truck percentages *(125)*. With all these findings, the Hoosier Helper program currently uses three response vehicles to cover the patrol area at peak hours while two patrol vehicles are deployed at off peak hours and at nights. The researchers advised that higher savings can be obtained if the deployment schedule is modified as well as improving the areas of operations, beat design and fleet size *(125)*.

Earlier studies provide valuable guidance on factors that need to be considered for determining the need for freeway service patrols and deployment of their services. However, localized studies are also important to better capture state need and reflect local conditions and needs in the decision-making process, both during the planning, and deployment phases.

2.5.7. Summary

The service patrol deployment tools we studied relied on predictive models to estimate the number of incidents on a given highway segment and therefore the need for service patrols. Like the incident factor model currently used by ALDOT, other states use a combination of segment length, AADT, number of reported incidents, and in some cases road geometry and truck volumes to determine the need for service patrols.

2.6 Conclusion

The state of TSMO implementation in the Southeast demonstrates inroads into new and emerging technologies, especially with the advent of connected and automated vehicles. Furthermore, established operational strategies continue to be effectively used in response to non-recurrent congestion, and they continue to be reliable tools for state agencies. As capacity constraints become more important factors in the decision-making process for investment, it is likely that Southeastern agencies will continue to implement proven strategies and expand their use of piloted strategies into the future. This review demonstrates the breadth of options currently adopted by these states, and recent TSMO plans show significant interest into investigating new technologies by state agencies *(4, 70)*. However, the benefits gained by different agencies by implementing different strategies are still unknown. A first step for determining their warrant and effectiveness for a corridor is to assess the incident occurrence rate and how much of that could be mitigated through such strategies. Because the occurrence of secondary crashes is closely related to the duration and congestion caused by a primary incident, it can be the target crash type for assessing the warrant and effectiveness of the strategies. With the availability of past incident and travel time data, we will address this matter by developing a secondary crash detection algorithm. We will also investigate whether actual measures of non-recurring congestion on freeway segments can be a better indicator of the need for service patrols.

3. Alabama Case Study

In this case study, we investigated the scope for improving the method developed by the Alabama Service Assistance Program (ASAP) for determining service patrol needs of a road. In it, we investigate the crash frequency and exogenous factors for assessing a service patrol program.

A recent study *(2)* conducted by the Alabama Department of Transportation (ALDOT) found that ASAP patrols significantly reduce incident clearance times. The study recommended that the service be expanded across the state. The Alabama DOT currently uses an incident factor (IF) method to determine where service patrols should be deployed. This method considers segment length, AADT, and the number of reported incidents occurring along a highway segment to determine whether service patrols are warranted. Under current policy, an IF score of four or above indicates that service patrols are warranted.

$$IF = \frac{(\text{AADT}) \ * \ (\text{average annual number of crashes/length of segment in miles})}{100{,}000} \qquad \text{Eq. 1}$$

The Alabama DOT has expressed interest in evaluating their criteria to consider whether other factors should be included, such as:

- Time of day
- Day of week
- Impacts of congestion to freight movement
- Roadway geometry

This study selected two interstate corridors in north Alabama, I-65 and I-565, and evaluated whether these additional criteria would impact ASAP deployment decisions. We used non-recurring congestion (NRC) rather than the number of reported incidents as the basis for segment evaluations. Using travel time data, we estimated the magnitude and costs of non-recurring congestion on individual highway segments from March 2021 to May 2021. These were then evaluated to determine whether changes to the current ASAP deployment and operations may be warranted.

The objective of this study was to determine whether considerations of roadway geometry, time of day, day of week, and freight movements would impact current deployment decisions for ASAP or similar services, or whether the existing criteria based solely on AADT and number of reported incidents is sufficient.

3.1 Methodology

ASAP service patrols currently operate on selected interstate corridors in and around the major metropolitan areas of Mobile, Montgomery, Birmingham, Tuscaloosa, and Huntsville, as shown in Figure 3-1. Two additional service areas along I-20 east of Birmingham and I-85 east of Montgomery cover the heavily traveled corridors to Atlanta. The patrols currently operate on weekdays only and during fixed times of the day. ALDOT expressed interest in determining whether these service patrols serve the state. Specifically, they would like to address the following questions:

- Are current service patrol corridors serving the areas of highest need and do they need to be expanded?
- For planning purposes, are there corridors that will likely need service patrols in the next five years?
- Are current patrol times adequate?
- Are there areas where service patrols should be expanded to weekends?
- Should priority be given to freight corridors, particularly those serving major industrial plants?

The IF offers a reasonably simple and efficient means of identifying candidate segments for service patrols, but it does not consider the time of day, day of week, segment geometry, or the presence of freight vehicles. Thus, the IF can provide only limited guidance for patrols, particularly regarding heavily traveled freight corridors.

Through our literature review, we found that the criteria used by other states for providing service patrols also rely on the number of incidents reported for a segment, AADT, and in some cases, segment geometry and truck volumes. These are predictive models based on several years of prior crash and volume data. As with Alabama's incident factor, they provide guidance on where service patrols should be instituted but little information regarding optimum service times or how freight movement is affected.

The goal of this study was to use readily available travel time data for state highways to estimate both the magnitude and costs of non-recurring congestion on interstate segments and allow that information to inform service patrol decisions. To demonstrate the methodology, we selected two interstate corridors in north Alabama, I-65 and I-565, which serve the Huntsville region. Estimates of non-recurring congestion in these corridors were developed for three months in 2021 and used to draw conclusions about service patrol needs.

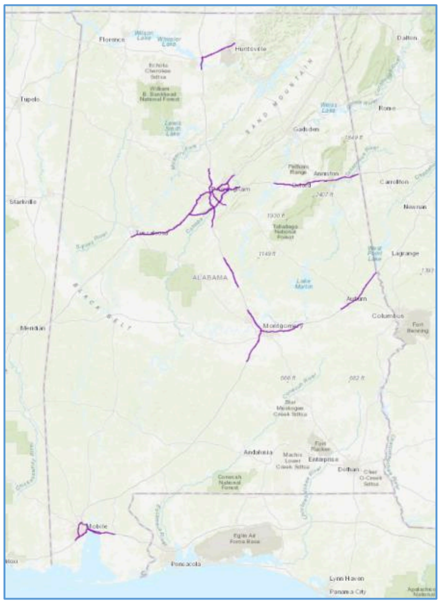


Figure 3-1: Current ASAP service patrol corridors, colored magenta (2022)

Service patrols will primarily impact the non-recurring events (e.g., crashes, disabled vehicles, and debris in the road), so this study focused on them as opposed to recurring or total congestion. However, non-recurring congestion can also include sources that service patrols are less likely to impact (e.g., roadway work zones and weather), so the analysis also attempted to account for them. The project produced a demonstration database that could be expanded statewide and used to provide annual performance indicators for all interstate segments and guidance on future ASAP deployments.

3.1.1. Study Corridors

For this study, we chose two interstate study corridors in the northern portion of Alabama:

Route	Segment	Length (miles)
I-65	Exit 318 (MM 318) to Tennessee State Line (MM 366)	48
I-565	I-65 (MM 0) to Exit 20 (MM 21)	21

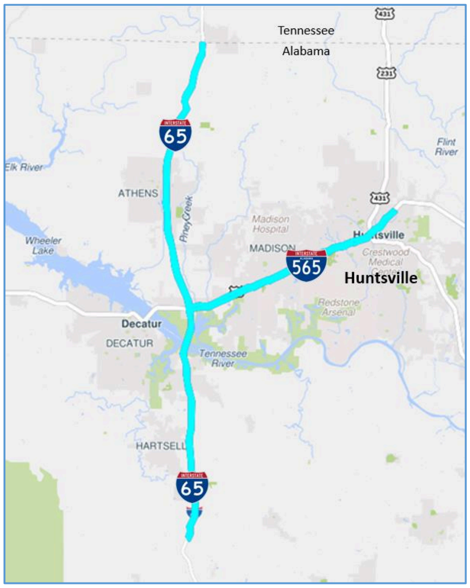


Figure 3-2: Study corridors (source: NPMRDS 2022)

The corridors were selected because they represent both primarily rural (I-65) and urban (I-565) sections. Most I-65 segments are rural, with two lanes per direction, and experience heavy truck volumes traveling between Alabama and Tennessee. I-565 is primarily urban, with close interchange spacing, complex interchanges, and high commuter volumes. The study corridors are illustrated in Figure 3-2.

As of 2022, all segments of I-565 have ASAP service patrols. Only a short segment of I-65 south of I-565 has ASAP patrols (from Exit 334 to Exit 340). See Table 3-1 for detailed information.

Table 3-1: Study segments and current ASAP service

Segment	From	To	Length(miles)	Remarks
I-65	Exit 318	Exit 322	4	No ASAP

Segment	From	To	Length(miles)	Remarks
I-65	Exit 322	Exit 325	3	No ASAP
I-65	Exit 325	Exit 328	3	No ASAP
I-65	Exit 328	Exit 334	6	No ASAP
I-65	Exit 334	Exit 340	6	ASAP
I-65	Exit 340	Exit 340 B	1	ASAP
I-565	Exit 1	Exit 20	21	ASAP
I-65	Exit 340 B	Exit 347	7	No ASAP
I-65	Exit 347	Exit 351	4	No ASAP
I-65	Exit 351	Exit 354	3	No ASAP
I-65	Exit 354	Exit 361	7	No ASAP
I-65	Exit 361	Exit 365	4	No ASAP
I-65	Exit 365	AL/TN Border	1.7	No ASAP

We identified the segment IDs, also known as the Traffic Message Channel (TMC) codes, for all segments in these corridors. As defined by the Traveler Information Services Association, these included both internal and external segments. TMC codes containing ‘P’ and ‘N’ typically denote segments within interchanges, while those with ‘+’ and ‘-‘ typically denote segments between interchanges. The ‘P’ and ‘+’ codes denote northbound and eastbound segments, while ‘N’ and ‘-‘ codes denote southbound and westbound segments.

The information for each TMC segment located within the study corridors included the TMC code, the road name, direction, intersection, presence or absence of ASAP service (represented with 1 or 0, respectively), the AADT for 2021, and truck percentage of total volumes. Data were downloaded from the National Performance Management Research Data Set (NPRMDS) (126). A sample of TMC data are shown in tables 3-2 and 3-3 below for I-65 and I-585, respectively. The complete datasets can be found in Appendix A.

Table 3-2: TMC segments and properties (I-65)

TMC. codes	Road	Direction	Intersection	Length (Miles)	ASAP Presence	AADT (veh)	Truck %
101P05053	I-65	NORTHBOUND	ALABAMA/TENNESSEE STATE LINE	0.050212	0	19749	40.00
101N05053	I-65	SOUTHBOUND	ALABAMA/TENNESSEE STATE LINE	0.050212	0	19749	40.00
101+05053	I-65	NORTHBOUND	AL--TN STATE BORDER	1.102879	0	19749	40.00
101-05052	I-65	SOUTHBOUND	AL-53/EXIT 365	1.159616	0	19749	40.00
101P05052	I-65	NORTHBOUND	AL-53/EXIT 365	0.574755	0	21054	38.28

101N05052	I-65	SOUTHBOUND	AL-53/EXIT 365	0.415673	0	21011	38.33
101+05052	I-65	NORTHBOUND	AL-53/EXIT 365	0.811883	0	22145	37.00
101-05052	I-65	SOUTHBOUND	AL-53/EXIT 365	1.159616	0	19749	40.00

Table 3-3: TMC segments and properties (I-565)

TMC codes	Road	Direction	Intersection	Length (Miles)	ASAP Presence	AADT (veh)	Truck %
101P04498	I-565	EASTBOUND	I-65/EXIT 1 & 1	0.393892	1	36391	9.00
101+04499	I-565	EASTBOUND	MOORESVILLE RD/EXIT 2	0.618797	1	62822	12.00
101-04499	I-565	WESTBOUND	MOORESVILLE RD/EXIT 2	1.647097	1	59717	10.00
101-04498	I-565	WESTBOUND	I-65/EXIT 1 & 1	0.584901	1	63650	12.00
101P04499	I-565	EASTBOUND	MOORESVILLE RD/EXIT 2	0.558442	1	61849	11.12
101N04499	I-565	WESTBOUND	MOORESVILLE RD/EXIT 2	0.600395	1	61584	10.98
101+04500	I-565	EASTBOUND	GREENBRIER RD/EXIT 3	1.636499	1	59717	10.00

3.1.1. Calculation of Traffic Volumes

Every TMC code in the NPMRDS has a 2021 Annual Average Daily Traffic (AADT) volume associated with it. In order to estimate non-recurring congestion-induced delays on the study segments, we needed traffic volumes with at least an hour resolution. To convert AADT volumes to hourly segment volumes, we used data from permanent count stations within the corridors to develop conversion factors that would allow us to estimate hourly volumes for typical weekdays and weekends in each segment. Because the number of permanent count stations was limited, the study segments were grouped into zones and sets of conversion factors were developed for TMCs within each zone. The count zones are summarized in Tables 3-4 and 3-5.

Table 3-4: Count station zones for I-65 segments

TMC ZONE	A	B	C	D
INTERCHANGES	354-366	351-354	325-328	310-318
COUNT STATION	831	250	56	55

Table 3-5: Count station zones for I-565 segments

TMC ZONE	E	F	G	H	I	J	K	L	M
INTERCHANGES	1-2	2-3	3-7	7-8	11-13	14-15	15-17	17-19	20
COUNT STATION	409	541	536	448	447	92	89	451	453

Each TMC was assigned two factors, f_{week} and f_{end}, that would allow for the conversion of its associated AADT to weekday and weekend ADT values.

$$f_{week} = \frac{ADT_{weekday}}{AADT_{tmc}} \qquad \text{Eq. 2}$$

$$f_{end} = \frac{ADT_{sat}}{AADT_{tmc}} \qquad \text{Eq. 3}$$

where ADT_{week} = Average Daily Traffic for weekday for a particular count station

ADT_{end} = Average Daily Traffic for Saturday for a particular count station

$AADT_{tmc}$ = Annual Average Daily Traffic for each TMC code

f_{week} = factor for converting AADT to weekday ADT

f_{end} = factor for converting AADT to weekend ADT

After assigning weekday and weekend ADT volumes to each TMC, another set of factors, $f_{hour,}$ was developed to allow the conversion of the ADT volumes to hourly volumes. The values for f_{hour}, 24 separate values for each hour of the day, were also derived from the permanent count station data and assigned to TMC's by zone. Using these, each TMC was given typical weekday and weekend-hourly volumes.

3.1.2. Quantifying Non-Recurring Congestion

Service patrols are primarily intended to mitigate non-recurring congestion and unpredictable incidents. Sources of non-recurring congestion can include crashes, disabled vehicles, debris in the roadway, construction and roadway maintenance, weather, and special events. Recurring congestion is typically caused when traffic demand exceeds available roadway capacity, leading to congestion that tends to recur at the same times and in the same places. This study focused on the occurrences of non-recurring congestion in the study corridors as indicators of the need for service patrols. It was noted that service patrols are typically deployed to address delays and safety risks resulting from crashes, disabled vehicles, and roadway debris and are less likely to affect delays from weather or roadway maintenance, so the data were also analyzed to estimate the portion of non-recurring congestion resulting from these causes.

Raw speed and travel time data were downloaded from the NPMRDS database and aggregated to 15 minute intervals for the three-month period, March-May 2021. These months were chosen because they were post-COVID and represented typical non-summer travel months. Travel time data reflected both passenger vehicle and truck speeds. The data fields downloaded for this study include the TMC code, length of the segment, date, time interval, average speed, reference speed, and historical average speed. The *average speed* is the speed of the vehicles that pass through the TMC for the time intervals under consideration. The *reference speed* refers to the free flow speed, which is the average speed a motorist would have traveled, assuming there were no congestion or other adverse conditions. The *historical average speed* is the typical speed for a TMC segment based on historical data. The recorded average speed was used to calculate the historical average travel time, while the reference speed was used in calculating the free flow travel time.

3.1.2.1 Speed Analysis and Congestion Characterization

Speed and travel time data were analyzed for each TMC segment to identify periods of congestion. Significant speed reductions could be the result of recurring congestion, non-recurring congestion, or a combination of both. To account for normal fluctuations in travel speeds, the minimum threshold for a TMC segment to be considered congested was 90% of free flow speed. Once a TMC segment was identified as congested during any 15-minute period, the data was analyzed to determine what portion of the congestion was recurring and what was likely non-recurring.

When congestion was identified on a highway segment, a Standard Normal Deviate (SND) method was used to determine whether non-recurring congestion was present. This method uses the following formula to compute a standard normal deviation value on each TMC segment for each 15-minute interval during the study period.

$$SND_{ij} = \frac{Speed_{ij}}{Std\ deviation_i} \qquad \text{Eq. 4}$$

Where:
SND_{ij} = Standard Normal Deviate of a TMC at time interval i for day j
$Speed_{ij}$ = Speed of the TMC code at time interval i for day j
i = 15-minute interval
j = day of month

A database was created that contained the reported speed values for each TMC segment at 15-minute intervals over the three-month study period. These were used to compute average weekday and weekend speed values as well as weekday and weekend standard deviation values for each 15-minute period on each TMC segment. These were then used to compute an SND value for each TMC segment for each 15-minute period over the three months of data. Previous research by Sullivan et al. found that SND values of less than -1.5 typically indicate the presence of non-recurring congestion *(127)*. Non-recurring congestion can be accompanied by recurring congestion, so the next steps quantify the magnitude of both sources.

3.1.2.2 Quantifying Average Non-Recurring and Recurring Delays

If a TMC segment was determined to have congestion present, one of three conditions was assumed to exist: 1) all congestion was recurring, 2) all congestion was non-recurring, or 3) both recurring and non-recurring congestion was present. For condition 1, if congestion was detected on a TMC and the SND value was greater than -1.5, all congestion was assumed to be recurring. In these cases, the average recurring delay for a segment, measured in seconds, was calculated as the difference between the average travel time and the free flow travel time, where:

$$\text{Average travel time (in seconds)} = \frac{TMC\ length}{Average\ speed} * 3600 \qquad \text{Eq. 5}$$

$$\text{Free flow travel time (in seconds)} = \frac{TMC\ length}{Reference\ speed} * 3600 \qquad \text{Eq. 6}$$

$$\text{Historical average travel time (in seconds)} = \frac{TMC\ length}{Historical\ average\ speed} * 3600 \qquad \text{Eq. 7}$$

If congestion was detected on a TMC segment and the SND value was less than -1.5, either condition 2 or 3 was assumed to exist. In these cases, the average recurring delay for a segment, measured in seconds, was computed as the difference between the historical average travel time and the free flow travel time. Negative values were recorded as zero. The average non-recurring delay, measured in seconds, was calculated as the difference between the measured average travel time and the historical average travel time. In cases where all congestion was determined to be non-recurring, the value for the average recurring delay was zero.

3.1.2.3 Estimating Total Delays

Total delays for each TMC segment were estimated by multiplying the average recurring and average non-recurring delays by the 15-minute volume for each TMC. Average weekday volumes were used for Monday through Friday periods, and average weekend volumes were used for Saturday and Sunday periods. Thus, estimates for total vehicle hours of recurring delay and total non-recurring delay were assigned to each TMC for each 15-minute time interval. There are obvious limitations to these estimates in that average volumes are used throughout. First, they do not capture normal daily variations in traffic volumes on any given TMC. Second, during significant congestion events, motorists are likely to divert to alternate routes, and this is not captured in the average volumes. For the purposes of this study, however, which is trying to establish thresholds for ASAP service, it was felt this was a reasonable simplification.

3.1.2.4 Characterizing Non-Recurring Delays

Not all non-recurring congestion is of a type that would benefit from service patrols. Specifically, service patrols are unlikely to address delays caused by roadway maintenance, temporary work zones, or weather events. The occurrences of non-recurring congestion were therefore manually compared to ALDOT Traffic Management Center logs, maintenance logs, and weather data to determine the portion of the delays that were due to crashes and incidents, the portion due to roadway maintenance, the portion due to weather, and the portion due to other causes. These proportions were then used to determine the percentage of non-recurring congestion that could be addressed by service patrols.

3.1.2.5 Estimation of Congestion Costs

To better reflect the impact of congestion on freight movement, total segment delays were converted to total delay costs based on truck volume percentages and estimated costs per vehicle. Specifically, the costs of non-recurring congestion on a TMC were estimated as:

$$\frac{Sum\ of\ non{-}recurrent\ delay}{3600}\,([truck\ fraction*\$88.70] + [car\ fraction*\$13.97])$$

The above is based on an assumed delay cost to passenger vehicles of $13.97 per vehicle hour and a delay cost to freight vehicles of $88.70 per vehicle hour. The passenger vehicle delay cost is based on INRIX data. The average cost to freight vehicles includes a $63.70 cost to the vehicle operator, as estimated by ATRI, plus a $25.00 per vehicle hour cost to the industry in the form of delayed shipments and reduced productivity. For the purposes of this study, the truck delay cost used was admittedly somewhat arbitrary. Additional study would be needed to quantify the impacts of freight delays on industries within a corridor, particularly those relying on just-in-time production deliveries.

3.1.2.6 Determination of Service Patrol Needs

Total costs created by non-recurring congestion on each TMC over the 3-month study period were evaluated to determine the needs for service patrols and evaluate whether current service patrol areas, times of day, and days of the week are adequate or should be reconsidered. Recommendations for expanding this type of model to the other two-thirds of the state were then drawn from the analysis.

3.2 Alabama Case Study Results

The results of the congestion analysis are summarized for the following areas:

- Characterization of the causes of the non-recurring congestion in the study area
- Congestion by day of the week
- Congestion by time of day
- Considering the costs of congestion to freight movement
- Implications for service patrol deployment

Under each topic, the results are separated by interstate corridor to better reflect the implications for urban sections (I-565) and rural sections (I-65).

3.2.1. Characterization of Congestion Sources

Highway service patrols are used to reduce congestion, enhance safety, and assist stranded motorists. With respect to congestion, they are most effective in addressing non-recurring types of congestion, i.e., congestion resulting from crashes, disabled vehicles, and objects in the roadway. For this reason, this study quantified both recurring and non-recurring congestion in the study corridors. It focused on the magnitude of non-recurring congestion, which service patrols could directly address. However, non-recurring congestion can also result from causes such as weather and roadway maintenance, and these sources may be less impacted by service patrols.

We, therefore, analyzed the congestion data and attempted to assign the occurrences of non-recurring congestion to a primary cause:

- Roadway maintenance or work zones
- Weather (rain or sleet)
- Reported incidents (crashes or disabled vehicles)
- Non-reported incidents (minor crashes, disabled vehicles, or objects in the roadway)

ALDOT Transportation Management Center (TMC) logs were obtained for the period March-May 2021. This contained information on all reported incidents in the study corridors during this period, including incident date, reporting time, clearance time, incident location, mile marker, and a brief description of the incident type. We were able to correlate these to the non-recurring congestion data and estimate the total delay associated with each incident. All major incidents were clearly correlated with the congestion data, as were many of the minor incidents. Some minor incidents, however, did not result in non-recurring congestion significant enough to show in the congestion analysis. In these cases, the non-recurring congestion associated with the incident was noted as zero.

There was also a significant number of minor incidents that showed in the congestion data but were not noted in the ALDOT TMC logs. Typically resulting in only minor delays, these were noted as non-reported incidents and could have included disabled vehicles or minor road obstructions. We were not able to determine the exact causes of these minor incidents for this study.

The congestion data was also checked against weather logs (rain events), and each event's estimated non-recurring congestion was noted. Weather events can often be identified in the data as the simultaneous occurrence of non-recurring congestion across multiple roadway segments. Finally, estimated delays were assigned to roadway maintenance events, which frequently had durations of multiple hours. The breakdown of non-recurring delay sources for both I-65 and I-565 is shown in Figure 3-3 below for April 2021.

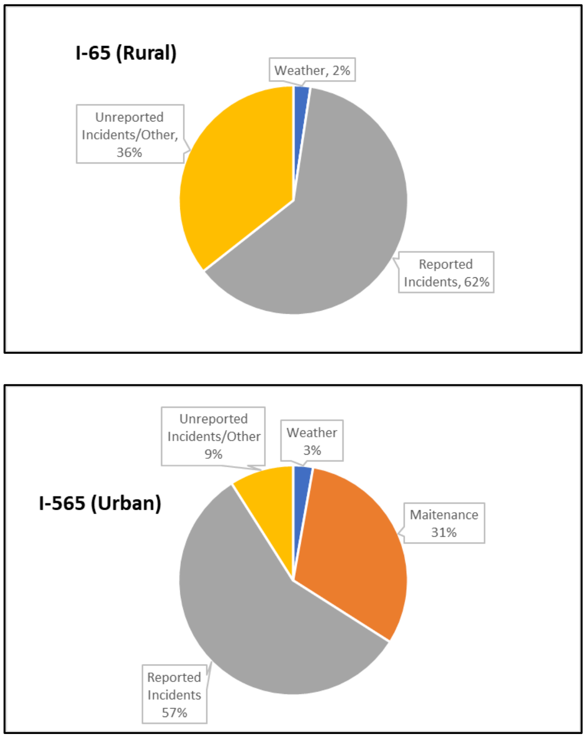


Figure 3-3: Sources of non-recurring delay in the study corridors

Several points can be noted:

- Weather accounted for less than 3% of total non-recurring delays during this study period.
- Roadway maintenance was a significant portion of the total non-recurring delay on I-565 during this period.
- A significant portion of the total non-recurring delay in both corridors was caused by non-reported incidents, from 9% along I-565 to 36% on I-65.

Our analysis was not able to identify the causes of the unreported incidents. However, it is important to note that service patrol deployment criteria that consider only reported incidents may be missing significant portions of total non-recurring delay. Regarding delays caused by roadway maintenance, for this period, it was only found on I-565, but it was a significant portion of the total non-recurring delay. Depending on the type of services provided by service patrol vehicles, work zone delays could be excluded from the analysis supporting deployment decisions. However, for the purposes of this study, the Alabama DOT specifically identifies work zone management as one of the services provided by their ASAP patrols, so delays related to work zones and highway maintenance were included in subsequent analyses.

3.2.2. Congestion Distribution by Day of Week

Total non-recurring delays were summed by day of the week for each of the study corridors. The purpose was to determine the distribution of non-recurring delays throughout the week so that the information could ultimately be used to determine the days of the week on which service patrols are needed. This information is shown in Figures 3-4 and 3-5.

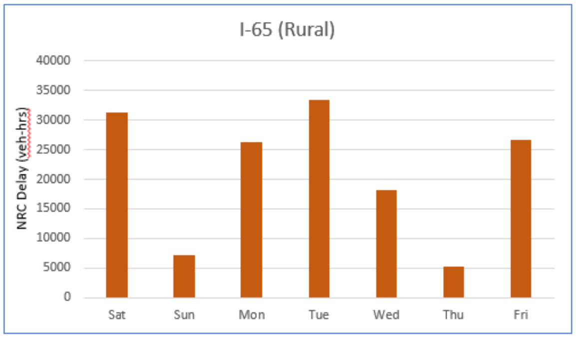


Figure 3-4: Distribution of NRC delay on I-65 by day (Mar-Apr 2021)

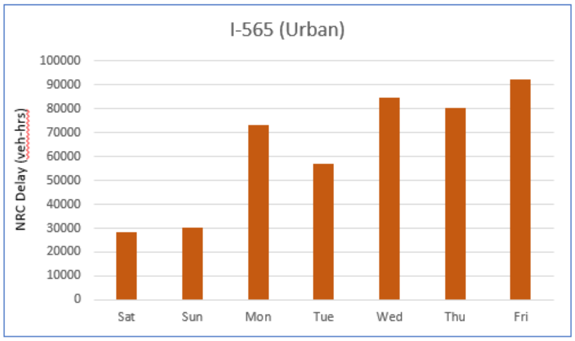


Figure 3-5: Distribution of NRC delay on I-565 by day (Mar-Apr 2021)

Non-recurring delay in the I-565 corridor, which is primarily urban, was clearly highest during the work week (M-F) and significantly lower on weekends. Non-recurring delay in the more rural I-65 corridor did not follow this pattern, with the second highest day-of-week total occurring on Saturday. When considering service patrols on rural highway sections, incident delays may not fall into traditional weekday/weekend patterns. The Alabama DOT does not currently provide service patrols on most segments of I-65 in the study area. However, should they expand patrols to this corridor in the future, these data could be helpful in determining service days.

3.2.3. Congestion Distribution by Time of Day

Total non-recurring delays were also summed by the time of day for each of the study corridors. The purpose was to determine the distribution of non-recurring delays throughout the day, so that the information could be used to determine the optimum times and frequency of service throughout the day. The distribution of non-recurring delays on I-65 is shown in Figure 3-6. The majority of incident-related delays occur between the hours of 08:00 AM – 7:00 PM. Though ALDOT does not currently provide service patrols through most of this corridor, the same information can also be provided at the TMC segment level should ALDOT consider expanding service patrols to a limited number of segments in this corridor.

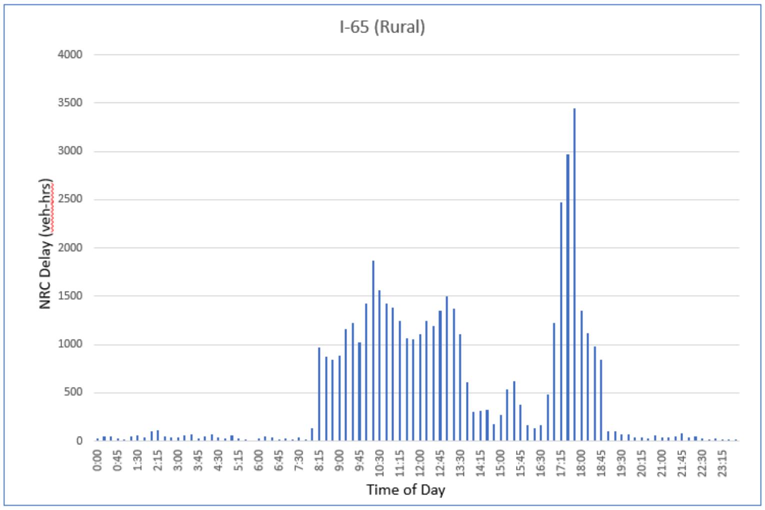


Figure 3-6: Distribution of NRC Delay on I-65 by the time of day (Mar-Apr 2021)

Figure 3-7 shows the non-recurring delay distribution in the I-595 corridor. This corridor currently has service patrols, so this information can be used to refine service times and frequencies. Non-recurring delays were more heavily concentrated in the afternoon hours and into the early evening. ALDOT currently provides service patrols in this corridor between 6:00 AM – 10:00 PM, so the data indicate that service patrols could possibly be operated at lower frequencies during the AM and midday periods.

Given that maintenance and weather delays comprised nearly 35% of all non-recurring delays in this corridor, we also looked at temporal distributions with weather and work zone delays removed. These are shown in Figure 3-8. It shows that much of the non-recurring delay in this corridor after 7:00 PM was work zone related. Whether this impacts service frequencies during those periods would be a policy decision for ALDOT. The current service patrol times in this corridor do appear adequate to capture most non-recurring delays. However, service frequencies could likely be adjusted throughout the day while maintaining sufficient service.

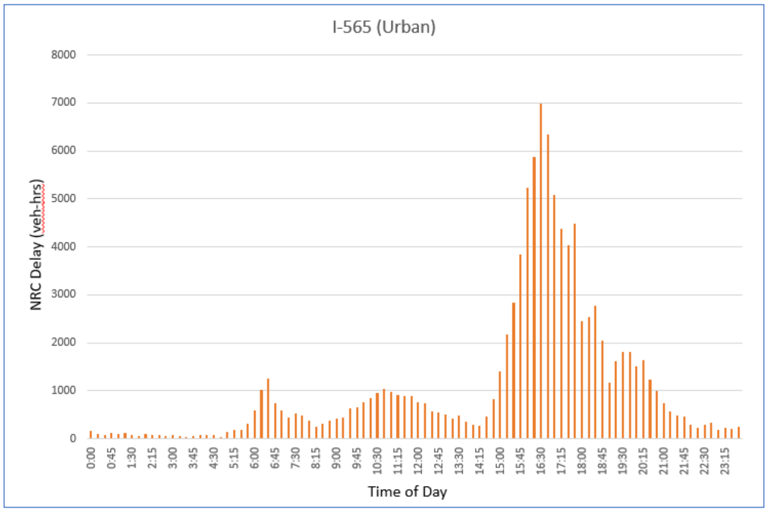


Figure 3-7: Distribution of NRC delay on I-565 by time of day (Mar-Apr 2021)

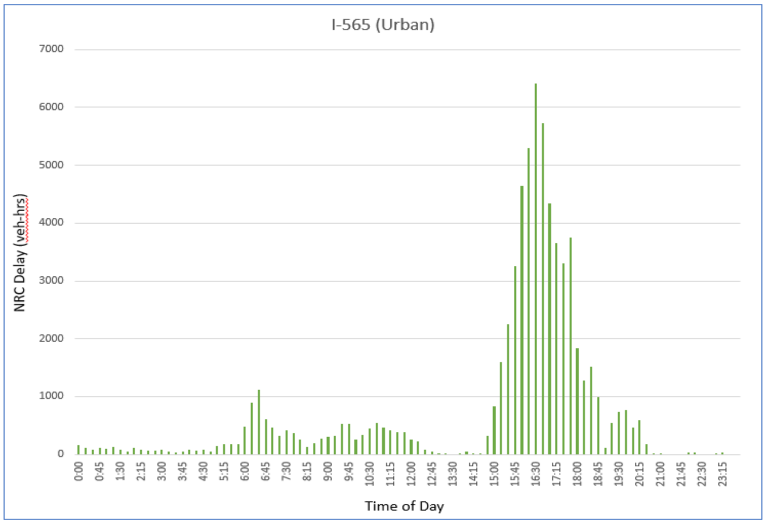


Figure 3-8: Distribution of NRC delay on I-565 (weather & work zones removed)

Temporal distributions of non-recurring delay could be a useful tool for state agencies to employ when determining service patrol times and frequencies. They could be particularly useful in drawing distinctions between service patrol frequencies on urban and rural highway sections, as the distributions of non-recurring delays may be quite different.

3.2.4. Cost Impacts on Freight Movement

The ALDOT criteria for providing service patrols currently do not consider truck volumes or the impacts of non-recurring congestion on freight movement and local industry. We, therefore, applied costs to the delays on each TMC based on % truck traffic. Delay costs of $13.97/hr were assumed for passenger vehicles and $88.70/hr for trucks. Total non-recurring delay costs were assigned to each TMC at 15-minute intervals for the three-month period from March through May 2021.

It is anticipated that non-recurring delay costs would be most useful in selecting highway segments for the deployment of service patrols. Figure 3-9 shows the total non-recurring delay for each TMC segment in the study corridors. Also shown are the current limits of the highway service patrols in this area. The figure shows total non-recurring delays (in veh-hrs) recorded during the 3-month study period. While the current service patrol limits seem to capture most of the critical segments, there are several segments along I-65 south of the current limits that may also warrant patrols. Figure 3-10 shows non-recurring delays over the same three-month period in terms of delay/mile, which normalizes the delays across different segment lengths. It also indicates that the current service patrol limits appear to be effective but that there may be justification to expand service to the south along I-65.

Figure 3-11 shows the total estimated non-recurring delay costs by TMC segment for the period March-May 2021. Figure 3-12 shows total estimated non-recurring delay costs per mile over the same period. Both figures suggest that when the cost of delays to passenger vehicles and trucks is taken into account, additional interstate segments may warrant the deployment of service patrols. In this case, high truck volumes on I-65 traveling between Nashville, Birmingham, and points south may merit additional service patrols.

3.2.5. Implications for Service Patrol Deployment

It should be noted that this report intentionally does not make recommendations for changes to current ASAP service patrol limits or service levels, as these decisions are best made by ALDOT with consideration of available resources. However, using travel time and volume data to estimate both the magnitude and costs of non-recurring congestion could offer state agencies like ALDOT a useful tool to identify deployment corridors for service patrols and better define service limits, service times, and service frequencies.

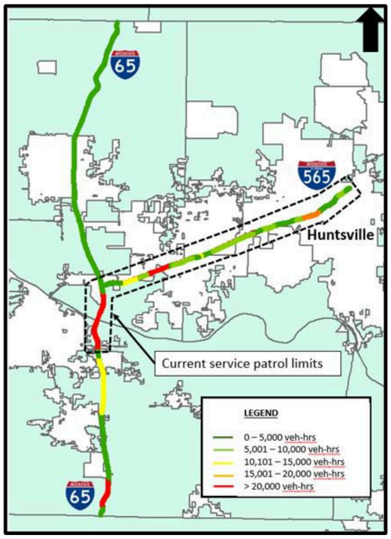


Figure 3-9: Total non-recurring delay by TMC segment (Mar-May 2021)

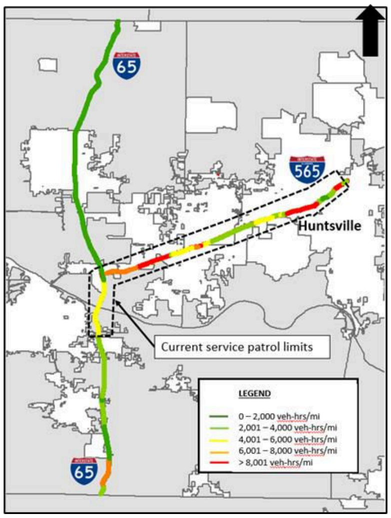


Figure 3-10: Total non-recurring delay/mi by TMC segment (Mar-May 2021)

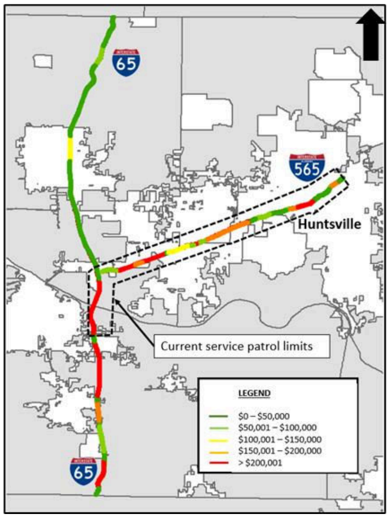


Figure 3-11: Total cost of non-recurring delay by TMC segment (Mar-May 2021)

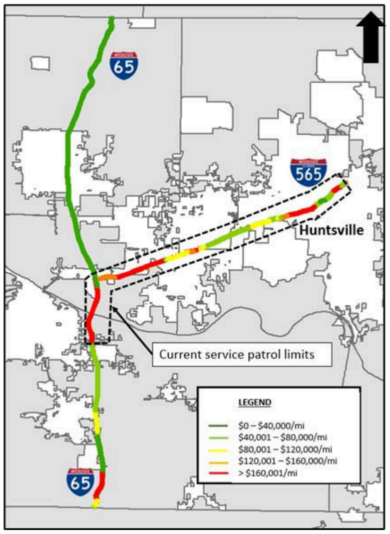


Figure 3-12: Total cost of non-recurring delay by TMC segment (Mar-May 2021)

3.2.6. Summary

The Alabama DOT currently uses decision criteria for the deployment of ASAP services that consider only reported incidents, AADT, and route segment length. This study examined two interstate corridors in north Alabama, one urban and one rural, to evaluate whether the current criteria are adequate to identify corridors that warrant service patrols and whether travel time data can provide additional information that will allow ALDOT, and other state agencies, to make better-informed decisions about service corridors, limits, service times, and service frequencies. Based on our analysis of 3 months of travel time data for approximately 70 miles of interstate corridors we drew the following conclusions:

- Unreported incidents can account for a significant portion of the non-recurring delay in a highway corridor. Our study found that unreported incidents accounted for 9%-36% of total non-recurring delay measured in the study corridors. Decision criteria that rely solely on reported incidents to determine service patrol deployments may be missing significant sources of congestion.
- The distribution of non-recurring delay across days of the week differed for urban and rural interstate sections. In the urban corridor (I-565) analyzed for this project, estimated non-recurring delays were highest Monday – Friday and significantly lower on weekends. On the rural interstate segments (I-65), there was no clear pattern for the distribution of delays.
- Travel time data and delay estimates can provide a useful tool for determining service patrol operation times and service frequencies.
- Estimates of delay costs that consider truck volumes and the impacts of delays on freight movements may help identify lower volume highway segments that nonetheless warrant service patrols. Rural segments with high proportions of trucks may warrant service patrols at significantly lower AADT's than urban routes.
- There is a significant initial cost to develop the database needed to analyze congestion and estimate congestion costs in highway corridors. However, once developed, the database can be easily updated with new travel time and AADT data so that annual evaluations can be made with minor additional costs.

This study analyzed only 3 months of travel time data. If this was expanded to 12-months, it could also provide information about seasonal variations in non-recurring delay and appropriate adjustments in service.

4. North Carolina Case Study

A major objective of incident management strategies, safety patrol deployment in particular, is to reduce the impact of incidents. Suppressing the incident impact in time and space also reduces the probability of secondary crashes (see Chapter 1 for definition). Therefore, the occurrence of secondary crashes on a corridor could be a key metric for determining service patrol needs and their effectiveness. Detecting secondary crashes is a challenging task, but with the availability of travel time and incident data, it is possible to detect the possible secondary crashes along with the related primary incident. Through this case study, we will demonstrate the development and application of a method for detecting potential primary-secondary incident pairs. A major interstate corridor in North Carolina is selected as the testbed. In addition, we will apply a crash-and-exposure-based metric identified in Chapter 2 to investigate the safety patrol need for that corridor.

4.1 Data Sources

The data we used in this study can be divided into three broad categories: i) incident data, ii) traffic operation (mainly speed) data, and iii) geometric data. We had two data sources for the first category, which are explained in the following subsection. The second dataset includes probe-based speed data, mainly used in this research to reveal traffic congestion location, time, type, and extent. The last dataset consists of the length of the study corridor, the location of the ramp junctions, and the traffic message channel (TMC) locations associated with the traffic operation data. These data are collected via Google Maps and Google Earth.

The data sources and their applications in this study are explained below.

4.1.1. Incident Data

One of the two incident data sources we employed in this effort is the incident archive, the traveler information management system (TIMS) maintained by the NCDOT. It contains detailed information on each disruptive event on the roads of North Carolina reported by an NCDOT operator. The key information included in the TIMS database are incident type (e.g., crash, work zone, or stopped vehicles), start and end dates and times, and start and end locations (both in geographic coordinates and mile markers). What cannot be known from this data are crashes that did not significantly impact the traffic flow and the extent of the associated congestion.

The second source is the crash data archived by the NCDOT through its Traffic Engineering Accident Analysis System (TEAAS). TEAAS includes detailed information on all the police-reported crashes in North Carolina, such as the location (in mile marker) and time. It also includes information on whether a crash was linked to a work zone. However, the database does not tell about the extent of the work zone or the impact of crashes on traffic flow.

It is evident from the description of the TIMS and TEAAS data that they supplement each other. One does not include all the crashes but has work zone information, whereas the other is a more comprehensive crash database but cannot describe work zone events.

4.1.2. Traffic Operation Data

As stated earlier, traffic operation data is vital to verify the occurrence and extent of traffic congestion between a pair of incidents. Our only source of traffic operations data is probe-based speed collected by HERE at certain spatial intervals called traffic message channels (TMCs) at 15-minute intervals. There is no direct information in this dataset on the cause of congestion; however, we classified it into recurrent and non-recurrent congestion using previously developed methods.

4.2 Data Preparation

Although combining the TEAAS and TIMS data and creating a comprehensive incident database would be ideal, the main challenge is removing duplicate events with differences in reporting techniques of incident time and location. Incidents in TEAAS are reported by the police in the field, while TIMS data are entered by the traffic operators who monitor camera feeds, probe data, third-party data like Waze, highway patrol reports, and iMAP radio monitoring. We found that the reported time and location for the same incident vary significantly in these two databases. Considering the difficulty of manually matching all the crashes between the two databases, we analyzed them separately. Traffic operation data were fused by matching the times and locations.

In this study, we removed long-term construction activities (duration of more than 24 hours) from the scope of the primary-secondary incident identification process. This is mainly because the algorithm involves the temporal relationship of each pair of incidents. A long-term incident would generate an unrealistic number of primary-secondary incident pairs.

4.3 Algorithm for Detecting Primary-Secondary Incidents

Starting with one of the incident databases, we investigate each pair of reported incidents' relative location, time, and direction to find the potential primary-secondary pairs. The following subsection describes the process. This exact process is repeated for both TEAAS and TIMS incident databases. We then employ the traffic operation data to verify if there was any queue between the incident pairs.

4.3.1. Potential Primary-Secondary Incident Pairs

Figure 4-1 shows the process flow for detecting potential primary-secondary incident pairs. The process is repeated for each reported incident in the database. The steps are described below.

- Step 1: Identify the temporal relationship

This step entails sorting the incidents by their start time and finding incident pairs that either temporally overlap with each other or the start time of the latter one is within a specific time interval of the end time of the former one. This time interval acts as a buffer to account for the effect of any residual queue that might have emanated from the first incident but existed even after that incident ended. Such a queue could have potentially caused the latter incident.

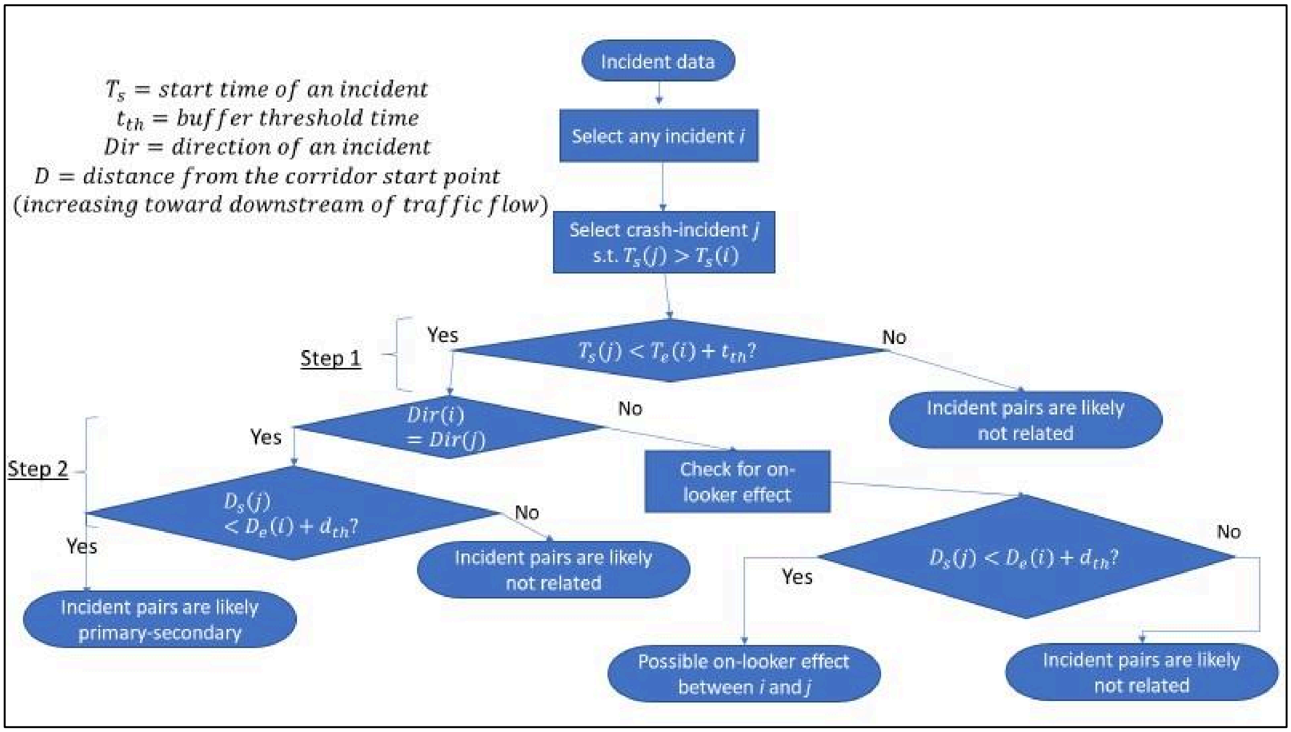


Figure 4-1: Algorithm for detecting potential primary-secondary incident pairs

The theoretical calculations of this buffer time depend on the shockwave speed of the queue; however, since such detailed data were unavailable to us, we used a fixed value of one hour as the buffer time. Figure 4-2 shows the temporal relationship of a hypothetical pair of incidents. The red bars show the duration of the incidents and the yellow bar shows the time buffer. The j^{th} incident occurred within the time threshold (t_{th}) of the end time of the i^{th} incident. Mathematically, the following condition must be satisfied to forward an incident pair to the next step of the process. Note that the i^{th} incident occurred earlier than the j^{th} incident. The value of t_{th} was chosen 60 minutes for the North Carolina case study.

$$T_s(j) < T_e(i) + t_{th}$$

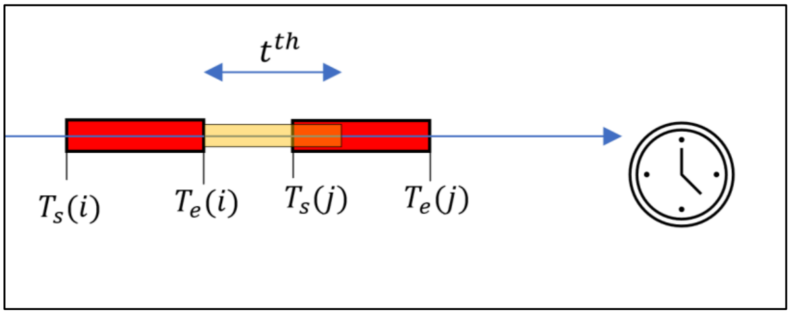
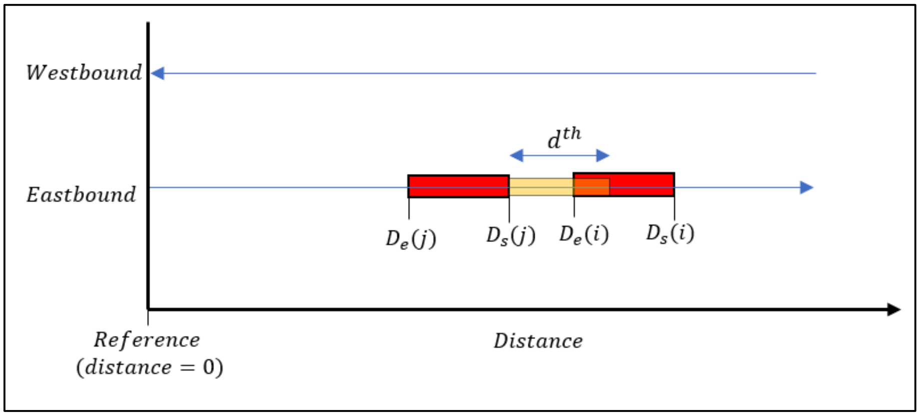


Figure 4-2: The timeline of an incident *i* and a later one *j.* The yellow bar extending from the end of incident *i* is the buffer time, indicating that crash *j* is within the influence of incident *i*

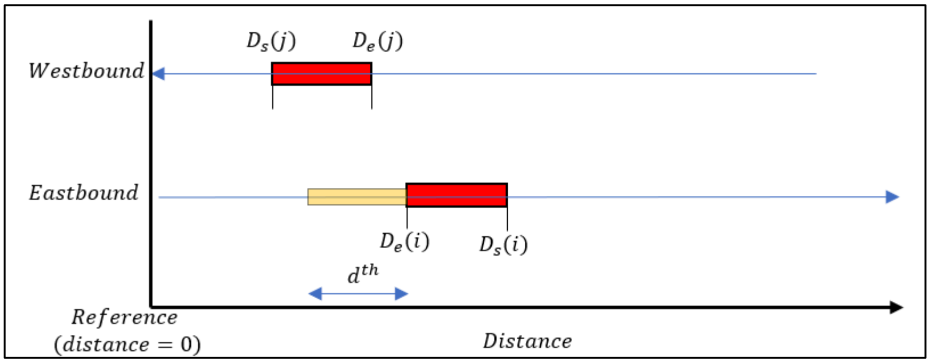
- Step 2: Identify directions and relative position

The relative distance of the incidents in each pair identified in Step 1 is estimated in this step. The concept is the same, although the direction and time of the incident pairs now come into play along with their distance. Suppose two incidents happen in the same direction of travel. In that case, the conditions that must be satisfied to consider them as a potential primary-secondary pair are i) the start location of the latter one must be upstream of (i.e., behind) that of the former one and ii) the distance between their spatial extent must be less than a certain distance threshold or their spatial extent must overlap.

Figure 4-3 (a) shows a hypothetical example of two incidents, where the latter one (i.e., the j^{th} incident) occurred upstream of (i.e., behind) the former one (i.e., the i^{th} incident). Moreover, although their spatial extents (shown by the red bars) do not overlap, the gap is less than the selected distance threshold (d_{th}).



(a)



(b)

Figure 4-3: Hypothetical examples demonstrating the relationship between two incidents in terms of time, distance, and direction. (a) for two incidents in the same direction, (b) for two incidents in opposite directions

If two incidents occur in opposite directions, there could still be a causal relationship between them because of on-lookers (aka rubbernecking effect). In this case, the conditions that must be satisfied to consider them as a potential primary-secondary pair are i) the start location of the latter incident must be upstream of that of the former one and ii) the distance between their spatial extent must be less than a specified distance threshold or their spatial extent must overlap. Note that for incidents in opposite directions, the relative location (i.e., upstream and downstream) is determined with respect to a fixed reference point.

Figure 4-2 (b) shows a hypothetical example of two incidents in opposite directions, where the latter incident (i.e., the j^{th} incident) occurs upstream of the former one (i.e., the i^{th} incident). Moreover, although their spatial extents (shown by the red bars) do not overlap, the gap is less than the selected distance threshold (d^{th}); therefore, they are considered as a potential primary-secondary pair.

Mathematically, the following conditions must be satisfied in this step to consider an incident pair as primary-secondary.

$$D_e(i) - d_{th} < D_s(j) < D_s(i)$$

The remaining events, i.e., those that do not meet the criteria described above, can still be a potential secondary incident since the primary cause can be a congestion event caused by high traffic demand or by an unreported incident.

4.3.2. Queue Check

The algorithm for detecting potential primary-secondary incident pairs (described above) considers only the spatiotemporal relationship of incidents; it does not consider any queue information. Typically, a secondary incident is caused by the queue emanating from the primary incident; hence, it is important to check if there was any queue between the potential incident pairs. To this end, we used probe-vehicle speed data from HERE, which reports the average speed at segment levels called traffic message channels (TMCs) by tracking "probes". Probes are vehicles with GPS devices, representing a certain fraction of the total traffic, that are tracked by data vendors like HERE which are used to estimate the average speed of a TMC.

We linked each shortlisted incident from the previous step to a TMC by matching their mile-markers. A GIS-based tool was used for this purpose. The presence of a queue between an incident pair can be verified by investigating the average speed (represented by a contour) of each of the TMCs at the date and time corresponding to the incidents. Also, there are several established methods for detecting congested TMCs (7–8). Most of them are based on comparing the observed speed against a threshold that is computed as a certain percentage of the free flow speed. Details on both approaches are discussed later in this chapter.

We also used the congestion scan tool of RITIS (*128*), which utilizes HERE speed data and visualizes the speed contour in time and space, to determine a reasonable value for the distance thresholds d_{th}. We investigated the congestion plot for each day when there was an incident and recorded the maximum queue length. It was found that the longest queue emanating from a bottleneck head was about 25 miles long, and thereby, we used this as the value for d_{th}. Figure 4-4 shows the speed contour plot for an extreme incident event over the day. Although this does not show the longest queue, it does show multiple congestion events with long queues to help illustrate the maximum spatial extent of congestion.

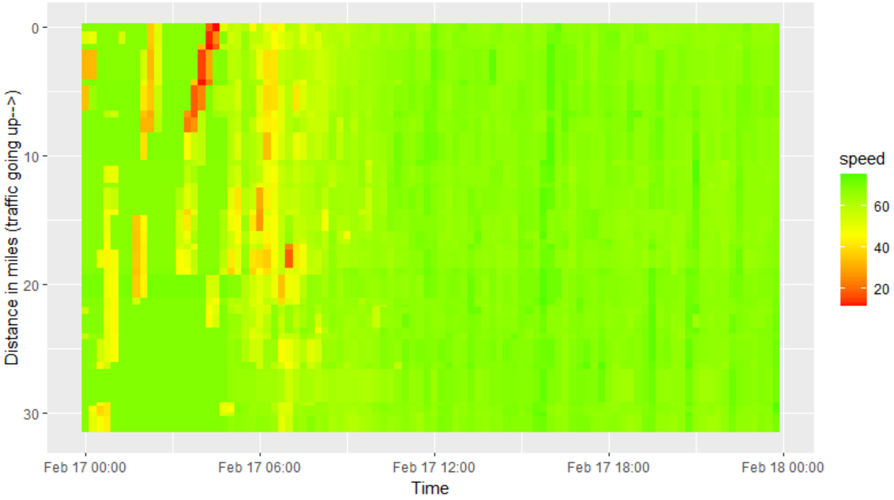
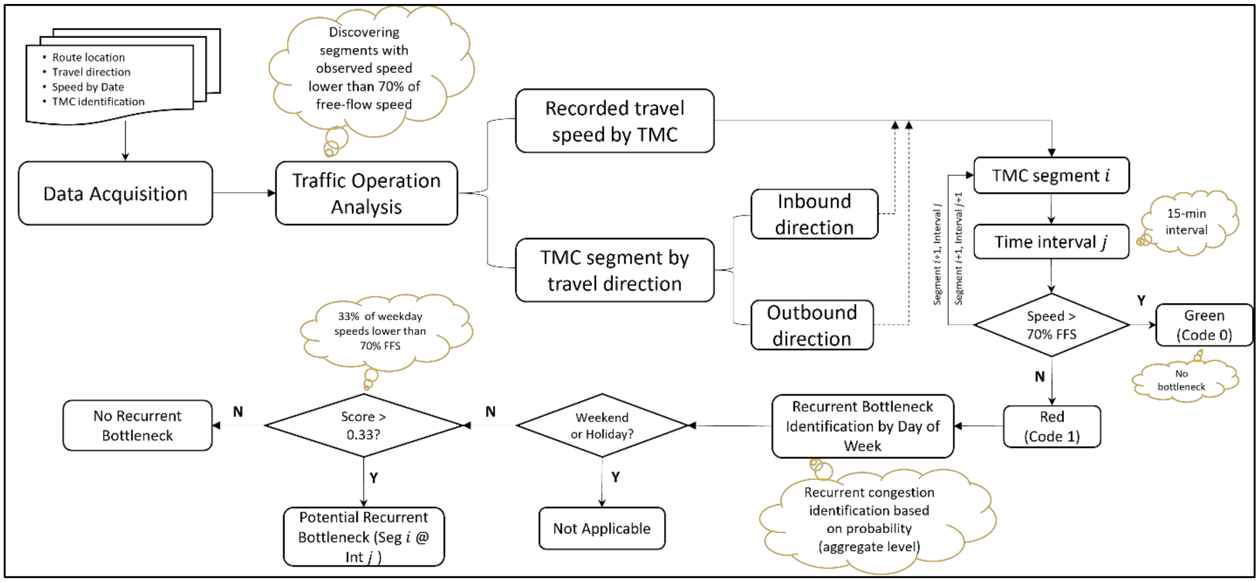


Figure 4-4: Speed contour plot in time and space for a day with extreme congestion

4.4 Recurring Bottleneck Identification Method

In order to quantify the impacts of secondary crashes that are caused by a non-recurring event, it is important to distinguish recurring and non-recurring congestion. The primary purpose of this analysis is to identify the potential recurrent bottleneck(s) along a study corridor. This is because the presence of a recurrent bottleneck may negatively affect the accuracy of identification of secondary crashes via travel speed or travel time data, since the reduction in average speed could be caused either by a crash or due to the presence of recurrent bottlenecks. In addition, distinguishing recurring and non-recurring congestion allows agencies to monitor TSMO strategies which may target these separately.

The operational analysis for identifying recurring bottlenecks is illustrated in **Figure 4-5**. The analysis method starts with acquiring probe-based traffic operational data for each study route from third-party agencies (e.g., INRIX, HERE.COM, etc.). The acquired data mainly includes travel direction, 15-min aggregated average speed by day, TMC identification, etc. To identify a potential bottleneck, our team first discovered segments (both inbound and outbound directions) with an observed speed lower than 70 percent of free-flow speed, which was found using the average speed at TMCs. For TMC segment i during time interval j, if the observed speed was larger than 70 percent of the free-flow speed, this segment was marked as Green and assigned a Code 0; otherwise, Code 1 was assigned with a red marker. Next, our team identified recurrent bottlenecks by day of week based on the assumption that for a TMC segment, the probability of having an average speed lower than 70 percent of the free-flow speed is not greater than one-third. Only non-holiday weekdays were considered for our effort as traffic volume during weekends and holidays is usually significantly lower than during weekdays. For each TMC segment, during each weekday and each time interval, the research team averaged the scores (i.e., "0" for non-congestion and "1" for congestion) of multiple observations across the analysis period (i.e., months or years). Finally, TMC segment i during time interval j could be identified as a potential recurrent bottleneck if the score is larger than 0.33.



4.5 Description of the Case Study Site

The North Carolina case study site we chose was Interstate 40/85, a freeway corridor between Greensboro and Hillsborough (Figure 4-5). The corridor is mostly east-west oriented, and we included both directions in the study. The unidirectional length is about 31 miles. The reason for choosing this corridor was that, unlike a city beltline, it does not experience demand-induced congestion at many interchanges on a daily basis. Therefore, it was possible to attribute congestion events to either incidents or high demand. At the same time, the corridor is important for freight and business since it acts as a connector between important cities of the state (including the capital Raleigh and the largest city, Charlotte). Incidents are also not rare and often cause severe traffic flow disruptions, as evident from the data analysis shown later in this report.

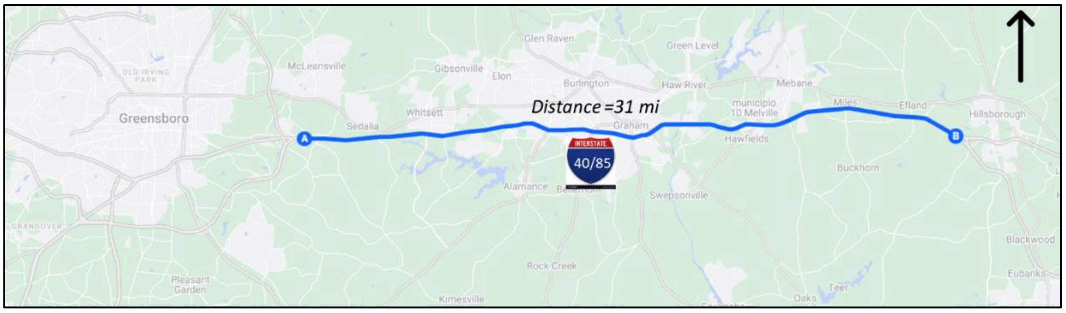


Figure 4-5: Location of the North Carolina case study corridor

4.6 Service Patrol Need Assessment

Under the Incident Management Assistance Patrol Program (IMAP), also known as the Safety Patrol, NCDOT deploy trucks equipped with specialized tools at select locations to relieve any kind of congestion *(130)*. The Safety Patrol covers certain highway routes during peak travel hours near Raleigh, Durham, Greensboro, Winston-Salem, Fayetteville, Wilmington, Charlotte, Asheville, and Haywood County. Figure 4-6 shows the location of service patrol deployments on the study site.

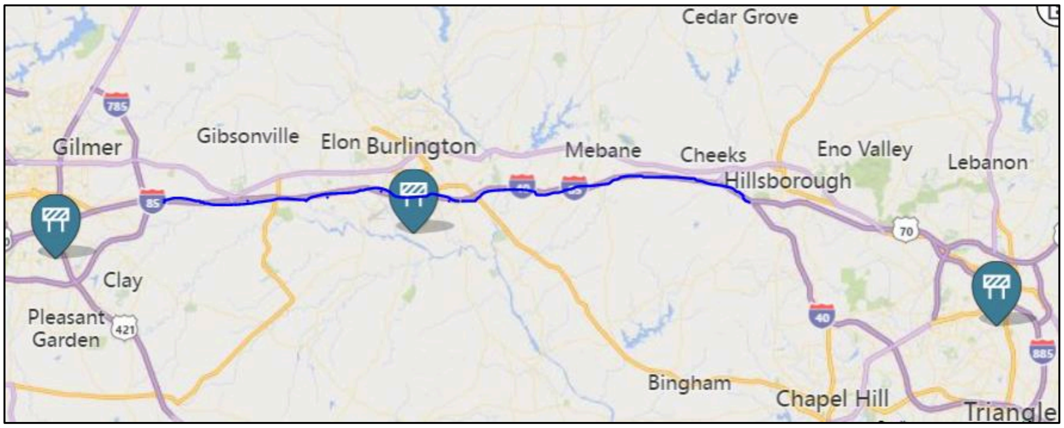


Figure 4-6: Service patrol areas on the case study corridor. Map markers indicate general locations and are not intended to represent actual service areas.

The strategy involved in the selection of the deployment location is not well-documented and varies by states. The Alabama Department of Transportation used a metric called Incident

Factor (IF) to identify corridors for service patrol deployment. It may play a major role in reducing secondary crashes. The analyses we showed on secondary crashes do not indicate whether or not the frequency of secondary crashes is high enough to warrant service patrols. Although IF was developed for Alabama roads, we estimated it for the NC case study corridor to determine the service patrol need.

The metric has been discussed in detail in Chapter 3. For better readability, the equation is repeated below.

$$IF = \frac{(\text{AADT}) \ * \ (\text{average annual number of crashes/length of segment in miles})}{100{,}000} \qquad \text{Eq. 8}$$

Under the ALDOT policy, $IF \geq 4$ indicates that service patrols are warranted. Note that we estimated the annual average crash frequency based on the six-month crash count in each direction of the corridor. AADT was estimated by averaging the AADT for each segment, weighed by the segment length. The NCDOT AADT web-map (*129*) provides the necessary data on segment AADT and segment lengths.

4.7 NC Case Study Results

4.7.1. Incident Data Description

In this section, we present the results from the North Carolina case study. As mentioned earlier, we used both the incident data from TIMS and crash data archived by the NCDOT. Those two are referred to as TIMS incident and archived crash database from this point onward.

The proposed method of detecting primary-secondary pairs of incidents is applied to the two databases separately because combining them was deemed difficult without bearing the risk of over-counting crashes. This issue is attributed to the fact that crashes that are common in both databases are complicated to spot due to the inherent differences in their reporting systems.

Although each database covered six months, their timeline differs, with the TIMS incident data spanning from January 1 to June 30 of 2016 and the archived crash database covering the same months but of 2015. The choice of the timeline was based on the availability of filtered crash data and congestion analysis tools—filtered crash data for the study site were available only for 2015. In contrast, the congestion analysis tool of RITIS (*128*) was available from 2016.

As mentioned earlier, the TIMS incident database contains incidents other than just crashes (see Table 4-1) and does not contain crashes that did not create many traffic disruptions. Table 4-1 shows the number of incidents reported in the TIMS database between January and June of 2016 on the study corridor by their category. Of the 169 reported incidents, 111 (66%) were confirmed crashes and 24 (14%) were unconfirmed crashes (i.e., congestion that *could have been* caused by a crash). The rests were disabled vehicles and maintenance and construction activities on the road.

Table 4-1: Number of reported incidents in TIMS by their category

TIMS Incident Category	Count
Crash (confirmed)	111
Congestion (unconfirmed crash)	24
Disabled Vehicle	9
Maintenance	21
Nighttime Construction	1
Nighttime Maintenance	3

On the contrary, the archived TEAAS crash database only contained crashes; however, a lot more than the TIMS database because any crash that satisfies the reporting criteria of NCDOT (131) was included in this database regardless of their impact on the traffic operations. In total 328 crashes were reported on the study corridor between January and June, 2015.

Another key difference in the reporting criteria of the two databases is that TIMS reports the start and end times for each incident, whereas the crash data archive only reports the first one, i.e., it has a single timestamp for each crash. On the other hand, neither database reports the start and end locations. The accuracy of the start and end times was questionable when compared to the HERE travel tie data; however, we used that data as is when applying the temporal threshold, as shown in Figure 4-2. For the archived crash data, we considered the red bars shown in that figure having a width of one hour, which is approximately the average duration of the incidents in this TIMS database (see Figure 4-7). For both databases, we considered the red bars representing the spatial extent of the incidents in Figure 4-3 as red dots.

Figure 4-7 shows the relative frequency of the TIMS incidents by their duration. Note that incidents with a duration of more than 24 hours were removed from the analysis. The mode of the incident duration, as depicted in this figure, is between 60-80 minutes; the average was found to be close to that as well. Approximately 7% of the incidents lasted for more than five hours; but more than 85% of the incidents were for two and a half hours or less.

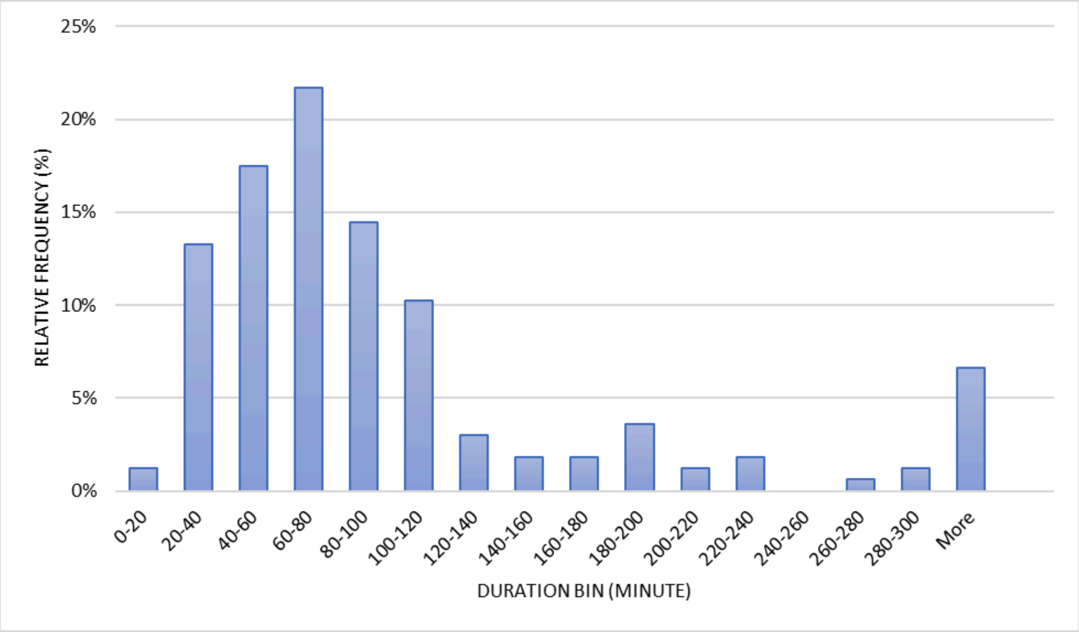


Figure 4-7: Distribution of duration of TIMS incidents

4.7.2. Potential Primary-Secondary Incident Pairs

Table 4-2 shows the results of applying the proposed method described in Figure 4-1 to the two incident databases. Of the 169 incidents reported in TIMS, 50 pairs were tagged as potential primary-secondary pairs. 47 of those 50 pairs contained both the primary and secondary incidents in the same direction and three in the opposite directions (implying that the secondary incident could have happened due to an on-looker effect). Note that some incidents were listed under multiple pairs. That is, 50 pairs of primary-secondary pairs do not mean that there are 50∗2 = 100 unique incidents in this list. Only 75 unique incidents were found to be either a primary or secondary incident.

On the other hand, when the same method was applied to the crash database, a smaller fraction of crash pairs were potential primary-secondary crashes. Out of 328 reported crashes, 59 pairs were shortlisted, three of which could have happened due to an on-looker effect in the opposing direction. This makes sense because the additional crashes in the crash database were not significant enough to trigger an iMAP event – a crash large enough to cause a serious traffic delay.

Table 4-2: List of potential primary-secondary pairs by data source

Data type	Description	Number
Incident data from TIMS (Jan-Jun, 2016)	Total reported incidents =	169
	Potential P-S pairs (same direction) =	47 (35 had congestion)
	Potential P-S pairs (opposite direction) =	3 (all had congestion)
Crash data from TEAAS (Jan-Jun, 2015)	Total reported crashes =	328
	Potential P-S pairs (same direction) =	56 (36 had congestion)
	Potential P-S pairs (opposite direction) =	3 (None had congestion)

For each potential pair, we analyzed the probe-based speed data obtained from RITS (*128*). Average speed data for each 5-minute interval were extracted for the periods and road segments associated with each incident pair. The objective was to look for congestion emanating from the primary to the secondary incident. A congested segment was defined as one with an average speed below 70% of the free flow or reference speed during a period.

The reduced number of paired incidents in the archived crash database is explained also by looking at the congestion data. The percentage of potential pairs in the crash database that showed congestion ($\frac{36+0}{56+3} * 100\% = 61\%$) was lower than that in the TIMS incident database ($\frac{35+3}{47+3} * 100\% = 76\%$).

4.7.3. Example Congestion Scan and Incident Plots

In this section, we will present the congestion plots for selected days when potential pairs of incidents took place. To this end, when generating the plots for incidents in the TIMS database, we used the *"Congestion Scan"* tool of RITIS to create the contour of average speed, overlaid by incident location and time. For the archived crash data, we replicated the visualization scheme of this tool in R—a free software environment for statistical computing and graphics (*132*)—since the RITIS tool only works with 2016 data.

Figure 4-8 shows the RITIS congestion scan plot for March 13, 2016, when three crashes took place. The first two incidents were tagged as a potential primary-secondary pair. The last one, starting more than an hour after the second one ended (i.e., after the temporal threshold was exceeded), was considered an isolated event. The yellow diamond signs in this figure show the crashes. The color from green to yellow shows the average speed at each 5-minute interval according to the scale in the top right corner. Traffic is going up, as shown along the vertical axis on the left. Here, the observer can see that following the first incident (approximately at 5:50 pm), the queue began to increase in length and a secondary crash occurred within the first hour (approximately at 6:45 pm) as the queue continued to grow. However, around 8:00 pm, the queue began to dissipate and a new primary incident occurred at approximately 8:45pm.

The second crash could have been attributed to the first one because it falls within the duration (shown by the horizontal black lines) of the first one. Moreover, the distance between them is only a mile and that road segment seems to be congested. A further downstream bottleneck could have caused the first crash because the bottleneck head is located just downstream of the crash location. The bottleneck head also activated slightly earlier than the occurrence of the first crash at around 5:35 pm.

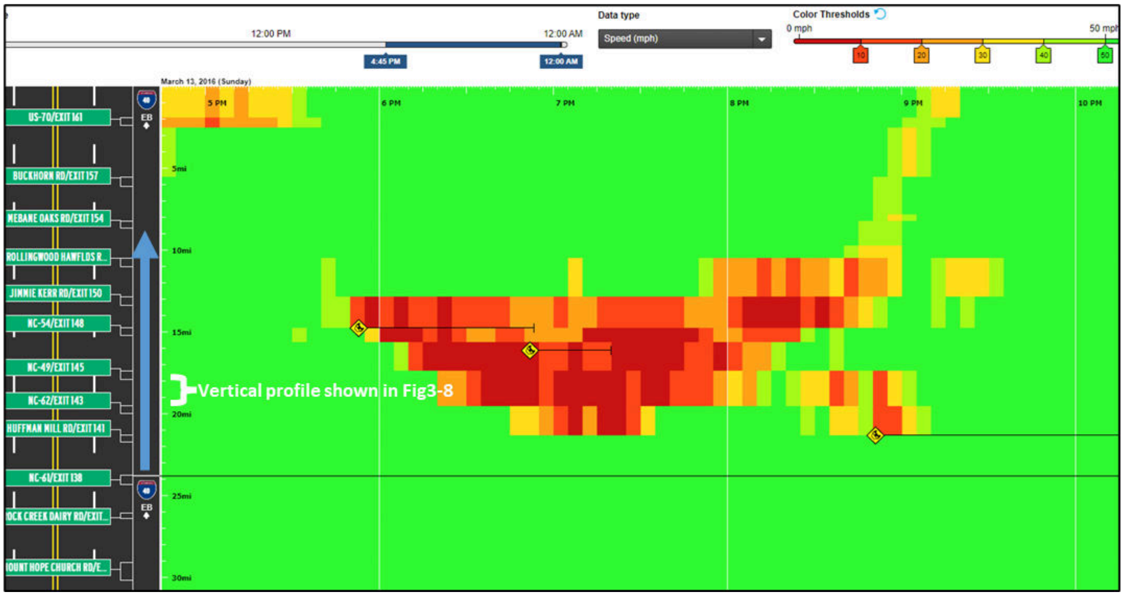


Figure 4-8: Congestion scan plot for a day overlaid with incident location and time

The third crash appears to be associated with a separate congested event that started later and downstream of the first one (i.e., traffic is moving between the two congested sections). However, it could also be associated with the first two since there is a chance that the initial congestion never got fully clear. Further investigations showed that the vertical grade of the segment between mile markers 18 and 16 consists of a sequence of crest and sag curves, with the highest slope being +3.3%. Figure 4-9 shows the vertical profile between those two points. Such steep grades restrict the sight distance of drivers, because of which they often hesitate to accelerate even if the congestion ahead of them gets cleared. Regardless, according to the definition of “congestion element” described by RITIS, the third crash falls under a separate element.

Figure 4-9: Vertical profile of the eastbound section between mile markers 18.5 and 16.5

Figure 4-10 shows the congestion scan for a day when there were four incidents reported in TIMS. Two disabled vehicles, indicated by a "D" inside the yellow diamonds in the westbound direction (left panel), one crash at a later period and further upstream in the same direction, and another crash in the eastbound direction but almost at the same time and location of the westbound crash. The proposed algorithm identified the two disabled vehicles as a potential primary-secondary pair. The two crashes on the opposite sides were also identified as a potential pair where the one on the eastbound direction acted as the primary incident and the one on the westbound could have been caused due to an on-looker effect.

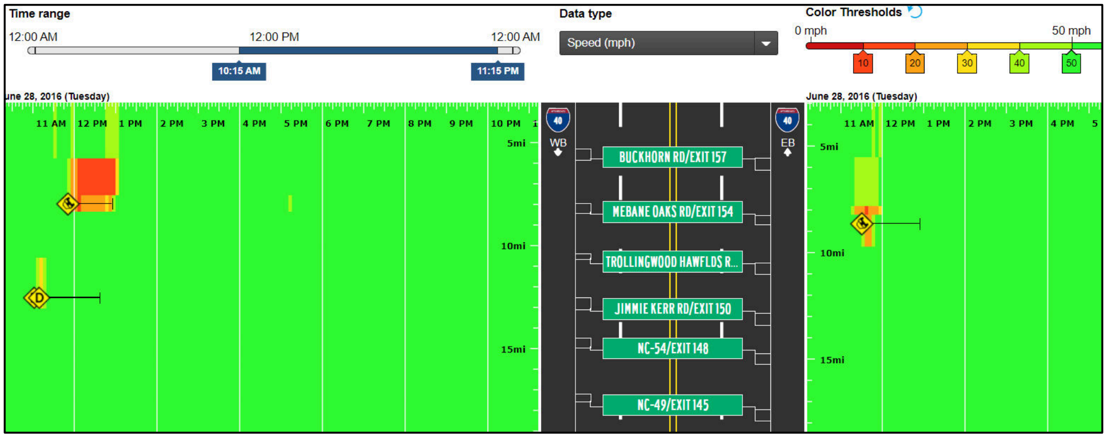


Figure 4-10: Example of possible on-looker effect and incident not creating congestion.

Figure 4-10 shows the congestion scan associated with two crashes that happened on January 14, 2015, as reported in the archived crash database. The plotting scheme, e.g., the color scale and the crash symbol (yellow diamonds) are slightly different in this plot compared to the output of the RITIS tool. Moreover, unlike the incidents reported in TIMS, the crash database does not report any *end time,* rather, it only reports the crash occurrence time.

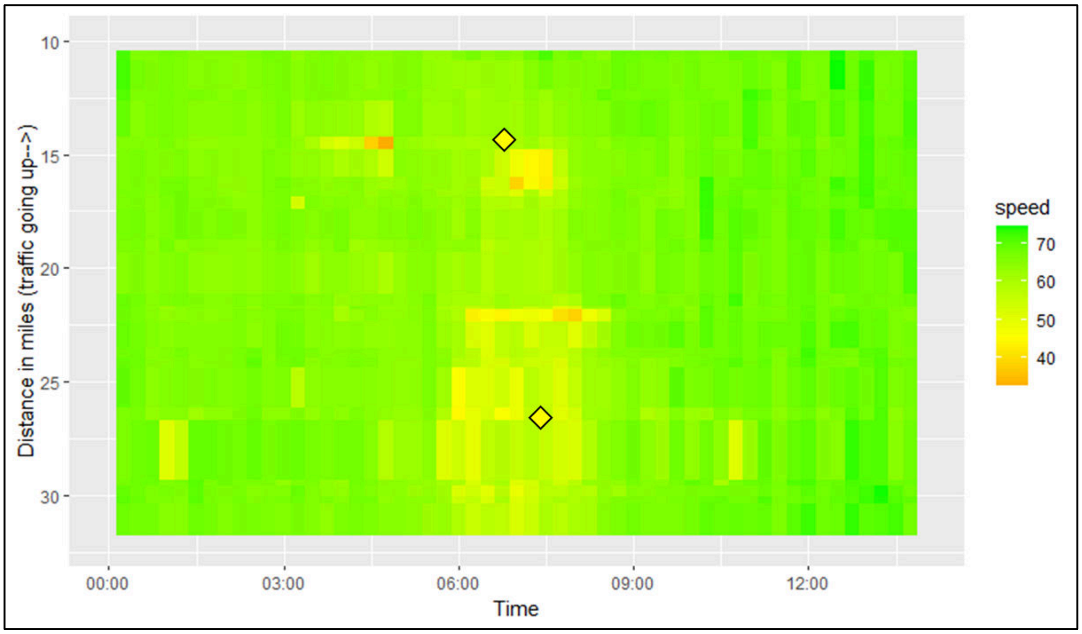
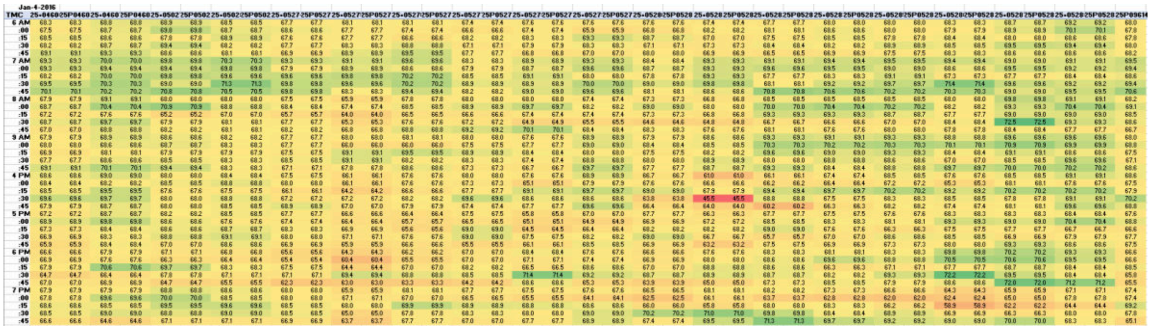


Figure 4-11: Congestion scan associated with two crashes with the intermediate spaces partially congested

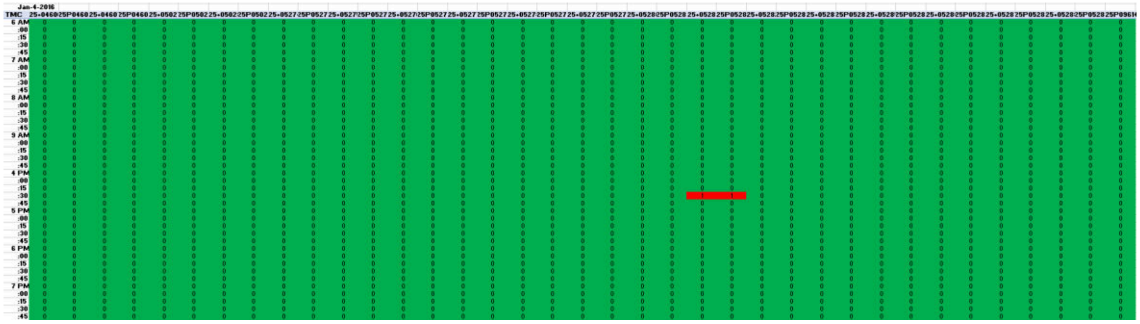
Figure 4-11 shows that the two crashes are about 13 miles and one hour apart. There are intermittent free-flow conditions on the road segments between them, which suggests that these two pairs are unrelated. However, there is a chance that the aggregated speed data were from a mixed-state period (i.e., a mix of congested and uncongested conditions), and some queue was still present on those apparently-congested segments.

4.7.4. Recurrent Bottleneck Identification

This section illustrates the results of recurrent bottleneck identification for the North Carolina case study corridor. The data analysis period ranges from January 2016 to June 2016. This research effort first identified and removed national or state holiday weekdays. Then, for each valid weekday, a spreadsheet was created for each travel direction where the columns are TMC stations in ascending order, and the rows are data analysis intervals (AM peak 6:00 – 10:00 and PM peak 16:00 – 20:00) in chronological order. Next, we employed an Excel pivot table to summarize the average speed for each TMC segment during each analysis interval. Eventually, the average speed table was converted to a binary parameter table where Code 1 represents speeds lower than 70 percent of the free-flow speed, and Code 0 represents speeds higher than 70% FFS. Figure 4-12 demonstrates an example of the data analysis processing results for a single weekday (i.e., Monday, January 4, 2016), where Figure 4-12(a) lists field collected 15-min average speeds by TMC segment for I-40 eastbound direction, and Figure 4-12(b) illustrated the binary codes for bottleneck identification. From Figure 4-12(b), it can be found that on this particular weekday, a bottleneck was identified for the eastbound direction between TMC # 125+05281 and TMC # 125+05282 during 16:30-16:45.



(a) Field collected 15-min average speed by TMC segment



(b) coded 15-minute average speed by TMC segment

Figure 4-12: Example of bottleneck identification for a single weekday

After processing average speeds for all Mondays, our team averaged the binary codes to identify recurrent bottlenecks, as shown in Figure 4-13. Results showed that no recurrent bottlenecks could be identified for both Eastbound and Westbound directions since all the scores are lower than 0.33. The same conclusion was made for the other weekdays, as Appendix B shows.

(a) I-40 Eastbound direction

(b) I-40 Westbound direction

Figure 4-13: Recurrent bottleneck identification for Mondays

4.7.5. Incident Factor

We feed the following information to Eq. 1 to estimate the incident factor for the entire corridor. Segment-by-segment calculation of the metric is shown in Table 4-3 below. Note that the corridor was divided into these segments by interchanges. Milepost = 0 is the westernmost point of the corridor.

*Segment length = 31*2=62 miles (total for both directions)*
Annual average crashes (both directions) = 656/year

Incident factor (IF) (both directions) = 11.9 (≥4)

Table 4-3: Segment-specific Incident Factor (IF) calculation

County name	Segment milepost range	AADT	Incident factor (both directions)
Guilford	0-3.3	123103	13.5
	3.3-5.7	121000	8.1
	5.7-7.2	119000	17.8
Alamance	7.2-8.2	119000	15.8
	8.2-9.9	124000	12.3
	9.9-12.1	123000	17.8
	12.1-13.8	120000	14.3
	13.8-14.8	117000	14.6
	14.8-16.6	111000	12.3
	16.6-18.9	106000	18.8
	18.9-21.3	100328	6.9
Orange	21.3-24	96000	8.5
	24-27.1	98000	8.2
	0-29.3	100013	12.9

The corridor-wide calculation shows that the IF value is very high for the study site, given the threshold greater than or equal to the four used by the ALDOT. Of course, this threshold is not calibrated to apply to North Carolina roads, but more than 300 crashes on six months and the high AADT values justify the IMAP service patrol deployment at this location.

The high magnitude of IF across different segments is evident from the segment-specific analysis. Even the lowest magnitude (6.9) is higher than the ALDOT threshold. Orange county has the major share of the study corridor; some of the segments with the highest IF are also located within this county (e.g., milepost 9.9–12.1 and 16.6–18.9). The corridor within the other two counties also has a few segments with IF >10.

5. Conclusions and Recommendations

The planning and monitoring of deploying mitigation strategies concerning unpredictable congestion can be improved if their sources and impacts on the transportation network are known. In the above case studies, we tested different frameworks to evaluate the impact and identify the cause(s) of unpredictable congestion events. Below are the key findings from this study.

5.1 Key Findings from Alabama Case Study

The Alabama DOT currently uses decision criteria to deploy ASAP services considering only reported incidents, AADT, and route segment length. This study examined two interstate corridors in north Alabama, one urban and one rural, to evaluate the current criteria for service patrol needs. Also, it examined whether travel time data can provide additional information that will allow Alabama DOT and other state agencies to make informed decisions about service corridors, limits, service times, and service frequencies. Based on our analysis of 3 months of travel time data for approximately 70 miles of interstate corridors, we drew the following conclusions:

- Unreported incidents can account for the significant non-recurring delay in a highway corridor. Our study found that unreported incidents accounted for 9%-36% of total non-recurring delay measured in the study corridors. Decision criteria that rely solely on reported incidents to determine service patrol deployments may be missing significant sources of congestion.
- The distribution of non-recurring delays across days of the week differed for urban and rural interstate sections. In the urban corridor (I-565) analyzed for this project, estimated non-recurring delays were highest Monday – Friday and significantly lower on weekends. On the rural interstate segments (I-65), there was no clear pattern for the distribution of delays.
- Estimates of delay costs that consider truck volumes and the impacts of delays on freight movements may help identify lower-volume highway segments that nonetheless warrant service patrols. Rural segments with high proportions of trucks may warrant service patrols at significantly lower AADTs than urban routes.
- A significant initial cost to develop the database is needed to analyze congestion and estimate congestion costs in highway corridors. However, once developed, the database can be easily updated with new travel time and AADT data to make annual evaluations with minor additional costs.

5.2 Key Findings from North Carolina Case Study

We developed a framework for identifying potential primary-secondary incident pairs in this case study. The method was applied to a 31-mile-long major interstate corridor using data covering six months. In addition, we assessed the need for service patrols for this corridor by applying the Alabama DOT method. Below are the key findings from this study:

- Two event databases were used separately. Fifty potential primary-secondary incident pairs were identified out of the 169 reported events in the Traveler Information Management System or TIMS incident database. Another database, the archived crash data, showed a lower percentage of pairs—59 pairs were identified out of 328 crashes.
- The difference in the outcomes concerning primary-secondary event pairs in the two databases is attributed to their reporting criteria—not all crashes are included in the incident database, and not all types of incidents are included in the crash database. Also, the location and time of the same event were found to vary significantly between them. The difference in data features could also contribute to the outcome differences. For instance, TIMS data included an incident's start and end times, whereas the crash database had only the occurrence time.
- We applied the congestion scan tool of RITIS to check for queues between a potential incident pair. The road between the pairs was fully or partially queued for 76% of the potential pairs identified in the TIMS database. The counterpart number for the crash database is 61%.
- We assessed the need for service patrol using the Incident Factor method developed by the Alabama DOT. The threshold Alabama DOT currently uses was met for all the segments. This finding justifies NCDOT’s decision to choose this corridor for the IMAP service patrol deployment.

5.3 Recommendations

- The applicability of the method we developed to identify primary-secondary incident pairs depends on the quality and content of the incident/crash database. One must carefully investigate them to avoid under or over-counting secondary events. For instance, the reporting criteria for crashes might influence the outcomes. Moreover, the crash location data can be erroneous for dense road networks where many roads may run close and parallel to the corridor of interest. Besides, application of the methodology to larger scale would require quickly pruning down the spatiotemporal areas to only non-recurring congestion.
- In the North Carolina case study, we could not demonstrate the use of recurring bottleneck data because there was none for the given study period. One can identify secondary crashes that were likely attributed to a recurring bottleneck activation using the proposed method simply by treating the recurring bottleneck as an incident (with known information about its time and location of activation).
- Detecting the cause of an incident is important to deploy targeted operational treatments. For instance, hard-shoulder running and variable speed limits are typically deployed to handle demand-induced congestion. On the other hand, treatments like rapid snow removal are specific to weather-related events.

- Although many public agencies are stepping back from releasing police reports of crashes due to data privacy issues, a few are still flexible in that regard. Those reports could be important in the context of detecting secondary crashes. Machine learning algorithms for text recognition can be applied to identify texts that suggest a causal relationship between two crashes.
- A full year of data could be useful to assess the impact of non-recurring delays by season. In Alabama, this could be particularly useful in the southern third of the state during peak summer tourism months.
- Processing multiple years of historical data could allow state agencies to identify trends and forecast service patrol needs several years into the future.
- The estimated congestion costs for freight vehicles likely need further study. Generic values were assumed for this study that were uniform across all interstate segments. Highway corridors that serve major just-in-time production facilities, for example, may merit higher delay costs.

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7. APPENDICES

7.1 Appendix A

Table A-7-1: TMC segments and properties (I-65)

TMC codes	Road	Direction	Intersection	Length (Miles)	ASAP Presence	AADT (veh)	Truck %
101P05053	I-65	NORTHBOUND	ALABAMA/TENNESSEE STATE LINE	0.050212	0	19749	40.00
101N05053	I-65	SOUTHBOUND	ALABAMA/TENNESSEE STATE LINE	0.050212	0	19749	40.00
101+05053	I-65	NORTHBOUND	AL--TN STATE BORDER	1.102879	0	19749	40.00
101-05052	I-65	SOUTHBOUND	AL-53/EXIT 365	1.159616	0	19749	40.00
101P05052	I-65	NORTHBOUND	AL-53/EXIT 365	0.574755	0	21054	38.28
101N05052	I-65	SOUTHBOUND	AL-53/EXIT 365	0.415673	0	21011	38.33
101+05052	I-65	NORTHBOUND	AL-53/EXIT 365	0.811883	0	22145	37.00
101-05052	I-65	SOUTHBOUND	AL-53/EXIT 365	1.159616	0	19749	40.00
101P05051	I-65	NORTHBOUND	ALABAMA WELCOME CENTER	0.458381	0	22145	37.00
101N05051	I-65	SOUTHBOUND	ALABAMA WELCOME CENTER	0.447748	0	22145	37.00
101+05051	I-65	NORTHBOUND	ALABAMA WELCOME CENTER	2.079141	0	22145	37.00
101-05051	I-65	SOUTHBOUND	ALABAMA WELCOME CENTER	0.914316	0	22145	37.00
101+05050	I-65	NORTHBOUND	SANDLIN RD/THACH RD/EXIT 361	6.041008	0	28299	44.00
101-05050	I-65	SOUTHBOUND	SANDLIN RD/THACH RD/EXIT 361	2.121131	0	22145	37.00
101P05050	I-65	NORTHBOUND	SANDLIN RD/THACH RD/EXIT 361	0.47439	0	25125	40.82
101N05050	I-65	SOUTHBOUND	SANDLIN RD/THACH RD/EXIT 361	0.44856	0	25494	41.23
101+05049	I-65	NORTHBOUND	US-31/EXIT 354	3.039139	0	25953	44.00
101-05049	I-65	SOUTHBOUND	US-31/EXIT 354	6.315942	0	28299	44.00
101P05049	I-65	NORTHBOUND	US-31/EXIT 354	0.393122	0	28299	44.00
101N05049	I-65	SOUTHBOUND	US-31/EXIT 354	0.5816	0	26812	44.00
101-05048	I-65	SOUTHBOUND	US-72/EXIT 351	2.500189	0	25864	44.00
101P05048	I-65	NORTHBOUND	US-72/EXIT 351	0.454266	0	29576	40.93
101N05048	I-65	SOUTHBOUND	US-72/EXIT 351	0.478469	0	28722	41.56
101+05048	I-65	NORTHBOUND	US-72/EXIT 351	3.008621	0	32494	39.00
101+53705	I-65	NORTHBOUND	HUNTSVILLE BROWNSFERRY RD	6.385974	0	32478	39.00
101-53705	I-65	SOUTHBOUND	HUNTSVILLE BROWNSFERRY RD	3.026587	0	32494	39.00
101P53705	I-65	NORTHBOUND	HUNTSVILLE BROWNSFERRY RD	0.690276	0	32486	39.00
101N53705	I-65	SOUTHBOUND	HUNTSVILLE BROWNSFERRY RD	0.730549	0	32487	39.00
101+05047	I-65	NORTHBOUND	I-565/OLD AL-20/EXIT 340B	5.87509	1	47391	27.00
101-05047	I-65	SOUTHBOUND	I-565/OLD AL-20/EXIT 340B	6.741528	1	32478	39.00
101P05047	I-65	NORTHBOUND	I-565/OLD AL-20/EXIT 340B	1.308693	1	39382	32.31
101N05047	I-65	SOUTHBOUND	I-565/OLD AL-20/EXIT 340B	0.644416	1	39516	32.21
101-05046	I-65	SOUTHBOUND	AL-67/EXIT 334	6.084927	1	47391	27.00
101P05046	I-65	NORTHBOUND	AL-67/EXIT 334	0.589749	1	45288	28.95
101N05046	I-65	SOUTHBOUND	AL-67/EXIT 334	0.491733	1	46076	28.20
101+05046	I-65	NORTHBOUND	AL-67/EXIT 334	5.30611	1	44235	30.00
101-05045	I-65	SOUTHBOUND	AL-36/EXIT 328	5.46671	0	44235	30.00

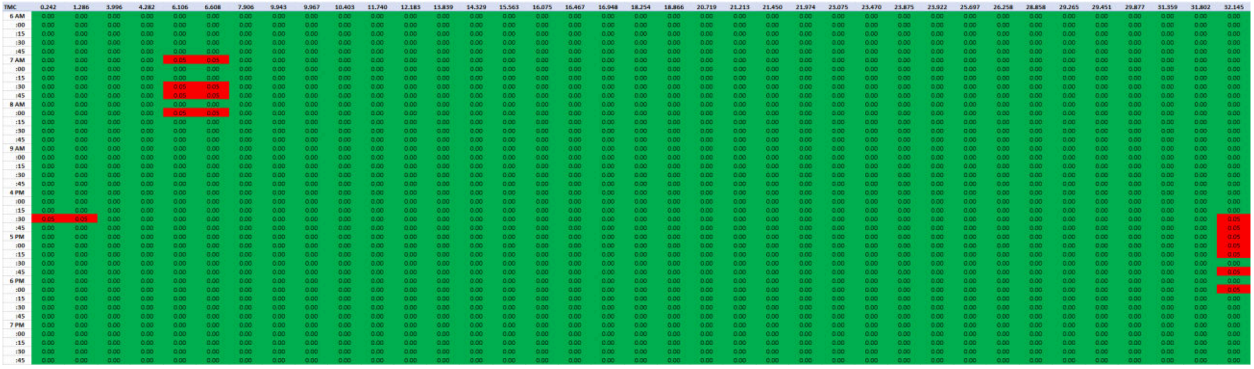
TMC codes	Road	Direction	Intersection	Length (Miles)	ASAP Presence	AADT (veh)	Truck %
101P05045	I-65	NORTHBOUND	AL-36/EXIT 328	0.373441	0	42622	30.00
101N05053	I-65	SOUTHBOUND	ALABAMA/TENNESSEE STATE LINE	0.050212	0	19749	40.00
101+05045	I-65	NORTHBOUND	AL-36/EXIT 328	2.064809	0	41190	30.00
101+05044	I-65	NORTHBOUND	THOMPSON RD/EXIT 325	2.496965	0	40836	19.68
101-05044	I-65	SOUTHBOUND	THOMPSON RD/EXIT 325	2.038501	0	41190	30.00
101P05044	I-65	NORTHBOUND	THOMPSON RD/EXIT 325	0.521914	0	41028	25.30
101N05044	I-65	SOUTHBOUND	THOMPSON RD/EXIT 325	0.510891	0	41030	25.36
101+05043	I-65	NORTHBOUND	CR-55/EXIT 322	3.115377	0	38626	31.00
101-05043	I-65	SOUTHBOUND	CR-55/EXIT 322	2.499513	0	40836	19.68
101P05043	I-65	NORTHBOUND	CR-55/EXIT 322	0.705883	0	39718	25.25
101N05043	I-65	SOUTHBOUND	CR-55/EXIT 322	0.715706	0	39717	25.26
101+05042	I-65	NORTHBOUND	US-31/EXIT 318	7.452181	0	37586	32.00
101-05042	I-65	SOUTHBOUND	US-31/EXIT 318	3.031052	0	38626	31.00
101P05052	I-65	NORTHBOUND	AL-53/EXIT 365	0.574755	0	21054	38.28
101N05052	I-65	SOUTHBOUND	AL-53/EXIT 365	0.415673	0	21011	38.33

TMC codes	Road	Direction	Intersection	Length (Miles)	ASAP Presence	AADT (veh)	Truck %
101P04498	I-565	EASTBOUND	I-65/EXIT 1 & 1	0.393892	1	36391	9.00
101+04499	I-565	EASTBOUND	MOORESVILLE RD/EXIT 2	0.618797	1	62822	12.00
101-04499	I-565	WESTBOUND	MOORESVILLE RD/EXIT 2	1.647097	1	59717	10.00
101-04498	I-565	WESTBOUND	I-65/EXIT 1 & 1	0.584901	1	63650	12.00
101P04499	I-565	EASTBOUND	MOORESVILLE RD/EXIT 2	0.558442	1	61849	11.12
101N04499	I-565	WESTBOUND	MOORESVILLE RD/EXIT 2	0.600395	1	61584	10.98
101+04500	I-565	EASTBOUND	GREENBRIER RD/EXIT 3	1.636499	1	59717	10.00
101-04500	I-565	WESTBOUND	GREENBRIER RD/EXIT 3	2.23584	1	63727	8.00
101P04500	I-565	EASTBOUND	GREENBRIER RD/EXIT 3	0.588649	1	61626	9.02
101N04500	I-565	WESTBOUND	GREENBRIER RD/EXIT 3	0.561014	1	62057	8.80
101+04501	I-565	EASTBOUND	AL-20/EXIT 5	2.120699	1	63727	8.00
101-04501	I-565	WESTBOUND	AL-20/EXIT 5	0.992157	1	63434	9.03
101P04501	I-565	EASTBOUND	AL-20/EXIT 5	0.163279	1	63727	8.00
101N04501	I-565	WESTBOUND	AL-20/EXIT 5	0.977783	1	63533	8.65
101+04502	I-565	EASTBOUND	GLENN HEARN BLVD/EXIT 7	1.664227	1	63489	8.80
101-04502	I-565	WESTBOUND	GLENN HEARN BLVD/EXIT 7	0.447941	1	63635	10.00
101P04502	I-565	EASTBOUND	GLENN HEARN BLVD/EXIT 7	0.492068	1	63523	9.46
101N04502	I-565	WESTBOUND	GLENN HEARN BLVD/EXIT 7	0.424859	1	63635	10.00
101+04503	I-565	EASTBOUND	WALL TRIANA HWY/EXIT 8	0.615687	1	63635	10.00
101-04503	I-565	WESTBOUND	WALL TRIANA HWY/EXIT 8	3.646089	1	79901	7.88
101P04503	I-565	EASTBOUND	WALL TRIANA HWY/EXIT 8	0.648762	1	69689	9.01
101N04503	I-565	WESTBOUND	WALL TRIANA HWY/EXIT 8	0.832569	1	72496	8.61
101+04504	I-565	EASTBOUND	AL-20/EXIT 13	3.566833	1	77189	8.00
101-04504	I-565	WESTBOUND	AL-20/EXIT 13	0.353346	1	106897	7.00
101P04504	I-565	EASTBOUND	AL-20/EXIT 13	0.354355	1	106843	7.00
101N04504	I-565	WESTBOUND	AL-20/EXIT 13	0.294058	1	106897	7.00
101+04505	I-565	EASTBOUND	AL-255/RIDEOUT RD/EXIT 14	0.301852	1	106897	7.00
101-04505	I-565	WESTBOUND	AL-255/RIDEOUT RD/EXIT 14	0.573229	1	118537	7.00
101P04505	I-565	EASTBOUND	AL-255/RIDEOUT RD/EXIT 14	1.119386	1	111775	7.00
101N04505	I-565	WESTBOUND	AL-255/RIDEOUT RD/EXIT 14	0.942738	1	114483	7.00
101+04506	I-565	EASTBOUND	OLD MADISON PIKE/EXIT 15	0.719327	1	118537	7.00
101-04506	I-565	WESTBOUND	OLD MADISON PIKE/EXIT 15	0.242277	1	118519	7.00
101P04506	I-565	EASTBOUND	OLD MADISON PIKE/EXIT 15	0.252259	1	118537	7.00
101N04506	I-565	WESTBOUND	OLD MADISON PIKE/EXIT 15	0.249822	1	118537	7.00
101+04507	I-565	EASTBOUND	SPARKMAN DR/BOB WALLACE AVE/EXIT 15	0.242118	1	118516	7.00
101-04507	I-565	WESTBOUND	SPARKMAN DR/BOB WALLACE AVE/EXIT 15	0.411929	1	117935	7.00
101P04507	I-565	EASTBOUND	SPARKMAN DR/BOB WALLACE AVE/EXIT 15	0.263412	1	117935	7.00
101N04507	I-565	WESTBOUND	SPARKMAN DR/BOB WALLACE AVE/EXIT 15	0.288614	1	117935	7.00
101+04508	I-565	EASTBOUND	AL-53/JORDAN LN/EXIT 17	0.419935	1	117935	7.00

TMC codes	Road	Direction	Intersection	Length (Miles)	ASAP Presence	AADT (veh)	Truck %
101-04508	I-565	WESTBOUND	AL-53/JORDAN LN/EXIT 17	1.161861	1	96756	6.00
101P04508	I-565	EASTBOUND	AL-53/JORDAN LN/EXIT 17	0.629222	1	105810	6.48
101N04508	I-565	WESTBOUND	AL-53/JORDAN LN/EXIT 17	0.825869	1	103276	6.35
101+04509	I-565	EASTBOUND	US-231/US-431/MEMORIAL PKWY/EXIT 19	1.268702	1	96756	6.00
101-04509	I-565	WESTBOUND	US-231/US-431/MEMORIAL PKWY/EXIT 19	0.087312	1	53248	7.00
101P04509	I-565	EASTBOUND	US-231/US-431/MEMORIAL PKWY/EXIT 19	0.54643	1	86300	6.15
101N04509	I-565	WESTBOUND	US-231/US-431/MEMORIAL PKWY/EXIT 19	0.508037	1	79346	6.27
101P04510	I-565	EASTBOUND	WASHINGTON ST/EXIT 19	0.523926	1	53248	7.00
101N04510	I-565	WESTBOUND	WASHINGTON ST/EXIT 19	0.437808	1	53248	7.00
101+04510	I-565	EASTBOUND	WASHINGTON ST/EXIT 19	0.080184	1	53248	7.00
101-04510	I-565	WESTBOUND	WASHINGTON ST/EXIT 19	0.036855	1	53248	7.00
101P04511	I-565	EASTBOUND	PRATT AVE/EXIT 19	0.228293	1	53248	7.00
101N04511	I-565	WESTBOUND	PRATT AVE/EXIT 19	0.354016	1	53248	7.00
101+04512	I-565	EASTBOUND	AL-20/OAKWOOD AVE/EXIT 20	0.336287	1	53248	7.00
101-04512	I-565	WESTBOUND	AL-20/OAKWOOD AVE/EXIT 20	0.704868	1	48117	7.00
101+04511	I-565	EASTBOUND	PRATT AVE/EXIT 19	0.00965	1	53248	7.00
101-04511	I-565	WESTBOUND	PRATT AVE/EXIT 19	0.331969	1	53248	7.00
101P04512	I-565	EASTBOUND	AL-20/OAKWOOD AVE/EXIT 20	0.522581	1	51134	7.00

7.2 Appendix B

(a) I-40 Eastbound direction



(b) I-40 Westbound direction

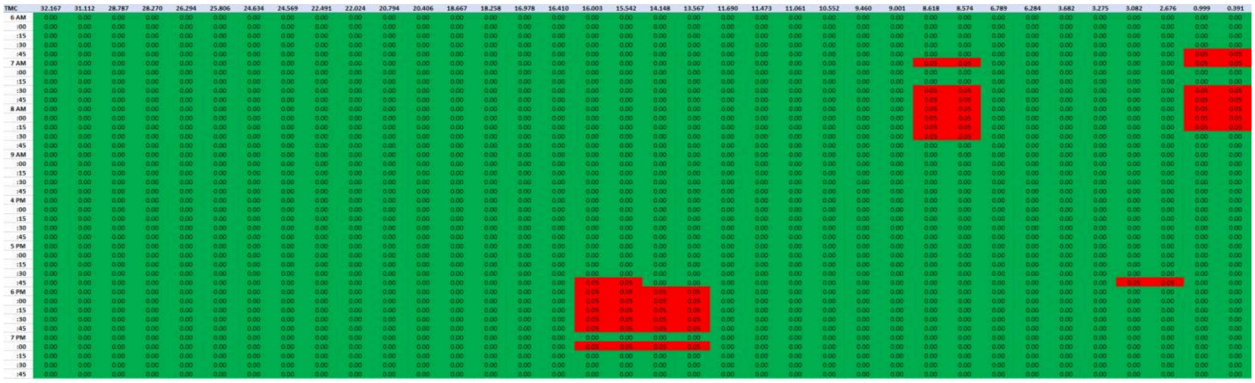
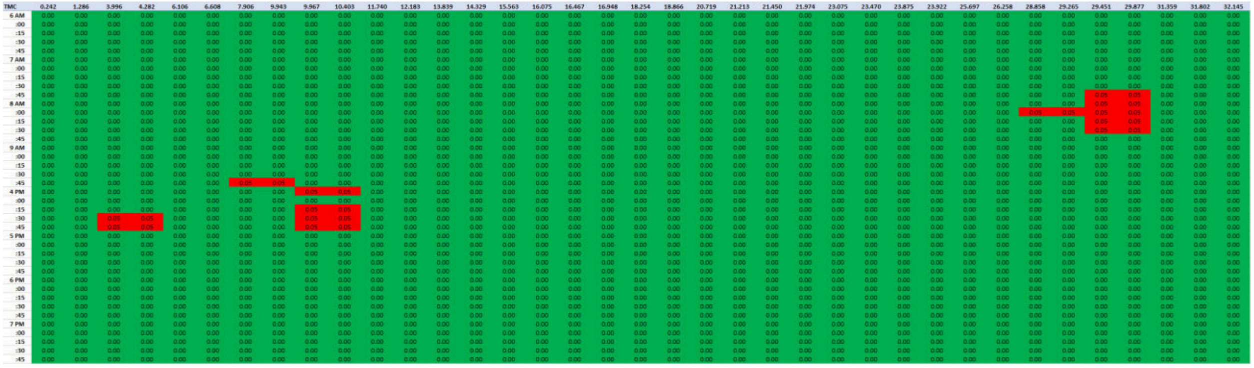


Figure B 1: Recurrent bottlenecks on the NC study corridor for Tuesdays

(a) I-40 Eastbound direction



(b) I-40 Westbound direction

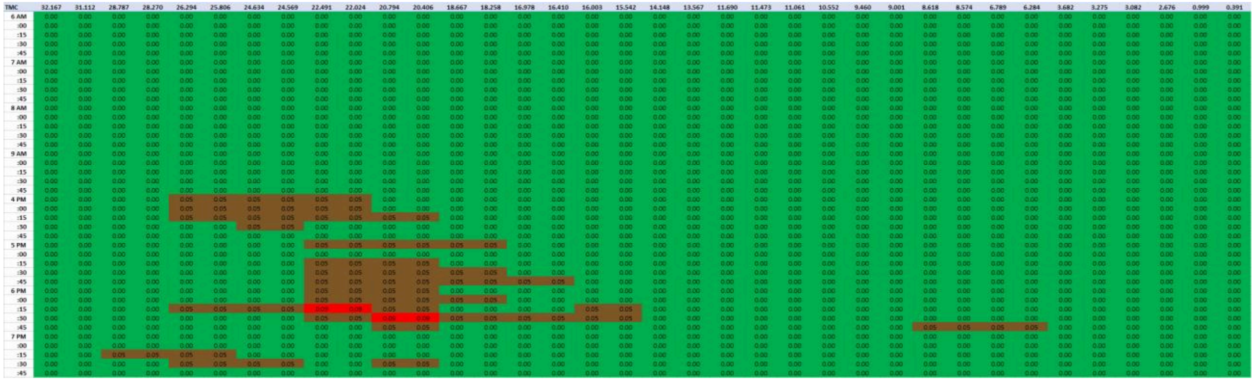
TMC	32.167	31.112	28.787	28.270	26.294	25.806	24.634	24.569	22.491	22.024	20.794	20.406	18.667	18.258	16.978	16.410	16.003	15.542	14.148	13.567	11.690	11.473	11.061	10.552	9.460	9.001	8.618	8.574	6.789	6.284	3.682	3.275	3.082	2.676	0.999	0.391
6 AM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7 AM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8 AM	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9 AM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4 PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5 PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6 PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7 PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure B 2: Recurrent bottlenecks on the NC study corridor for Wednesdays

(a) I-40 Eastbound direction

TMC	0.242	1.286	3.996	4.282	6.106	6.608	7.906	9.943	9.967	10.403	11.740	12.183	13.839	14.329	15.563	16.075	16.467	16.948	18.254	18.866	20.719	21.213	21.450	21.974	23.075	23.470	23.875	23.922	25.697	26.258	28.858	29.265	29.451	29.877	31.359	31.802	32.145
6 AM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7 AM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8 AM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00
9 AM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4 PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5 PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6 PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7 PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

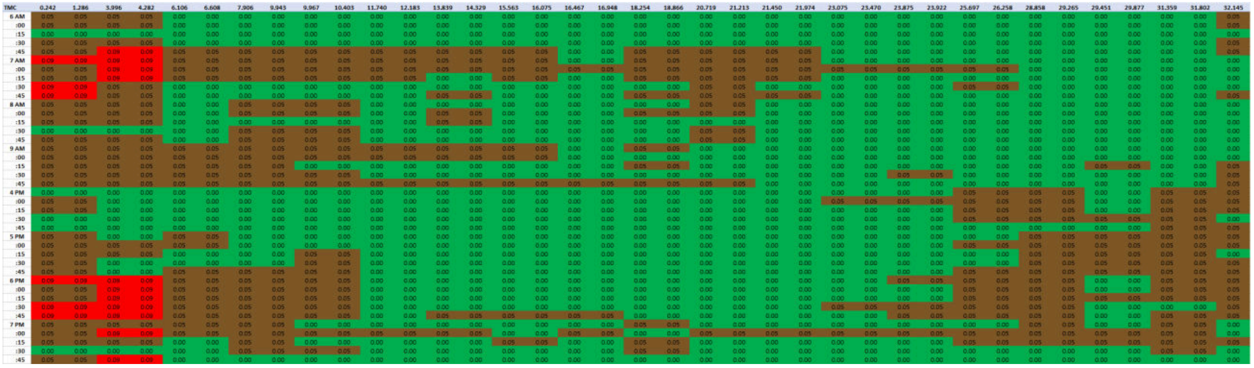
(b) I-40 Westbound direction



TMC	32.167	31.112	28.787	28.270	26.294	25.806	24.634	24.569	22.491	22.024	20.794	20.406	18.667	18.258	16.978	16.410	16.003	15.542	14.148	13.567	11.690	11.473	11.061	10.552	9.460	9.001	8.618	8.574	6.789	6.284	3.682	3.275	3.082	2.676	0.999	0.391
6 AM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7 AM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8 AM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9 AM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4 PM	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5 PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6 PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.09	0.09	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00
7 PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

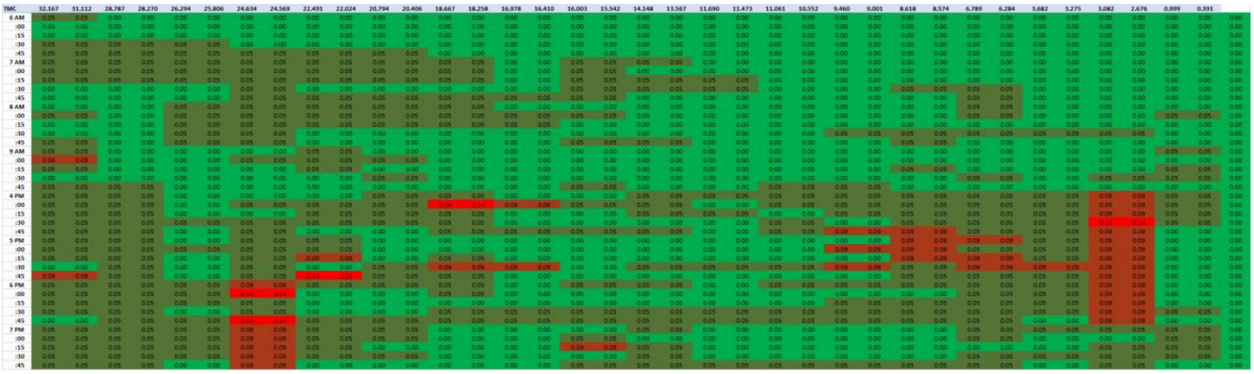
Figure B 3: Recurrent bottlenecks on the NC study corridor for Thursdays

(a) I-40 Eastbound direction



TMC	0.242	1.286	3.996	4.282	6.106	6.608	7.906	9.943	9.967	10.403	11.740	12.183	13.839	14.329	15.563	16.075	16.467	16.948	18.254	18.866	20.719	21.213	21.450	21.974	23.075	23.470	23.875	23.922	25.697	26.258	28.858	29.265	29.451	29.877	31.359	31.802	32.145
6 AM	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
:00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
:45	0.05	0.05	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
7 AM	0.09	0.09	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.05	0.05	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.05	0.05	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.09	0.09	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.09	0.09	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
8 AM	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9 AM	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.05
:30	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
:45	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
4 PM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05
:00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05
:15	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05
5 PM	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05
:00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
:15	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00
:30	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05
:45	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
6 PM	0.09	0.09	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05
:00	0.05	0.05	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05
:15	0.05	0.05	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
:30	0.09	0.09	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.05
:45	0.09	0.09	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05
7 PM	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.05	0.05	0.00
:00	0.05	0.05	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00
:15	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00
:45	0.05	0.05	0.09	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(b) I-40 Westbound direction



TMC	32.167	31.112	28.787	28.270	26.294	25.806	24.634	24.569	22.491	22.024	20.794	20.406	18.667	18.258	16.978	16.410	16.003	15.542	14.148	13.567	11.690	11.473	11.061	10.552	9.460	9.001	8.618	8.574	6.789	6.284	3.682	3.275	3.082	2.676	0.999	0.391	
6 AM	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7 AM	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:45	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8 AM	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:00	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.00
:15	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:30	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00
:45	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9 AM	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00
:00	0.09	0.09	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
:15	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00
:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.00
:45	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4 PM	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.05	0.05	0.00
:00	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.14	0.14	0.09	0.09	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.05	0.05	0.00
:15	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.05	0.05	0.00
:30	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.14	0.14	0.05	0.05	0.00
:45	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.09	0.09	0.09	0.09	0.05	0.05	0.05	0.05	0.09	0.09	0.00	0.00	0.00
5 PM	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.09	0.09	0.09	0.05	0.05	0.09	0.09	0.00	0.00	0.00
:00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.09	0.09	0.09	0.05	0.05	0.05	0.05	0.09	0.09	0.00	0.00	0.00
:15	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.09	0.09	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.09	0.09	0.09	0.05	0.05	0.09	0.09	0.00	0.00	0.00
:30	0.00	0.00	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.05	0.05	0.09	0.09	0.09	0.09	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.05	0.05	0.09	0.09	0.09	0.09	0.09	0.09	0.00	0.00	0.00
:45	0.09	0.09	0.05	0.05	0.00	0.00	0.05	0.05	0.14	0.14	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.00	0.00	0.00
6 PM	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.00	0.00	0.00
:00	0.05	0.05	0.05	0.05	0.05	0.05	0.14	0.14	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.09	0.09	0.00	0.00	0.00
:15	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.00	0.00	0.00
:30	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.05	0.05	0.00
:45	0.00	0.00	0.05	0.05	0.05	0.05	0.14	0.14	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.09	0.09	0.00	0.00	0.00
7 PM	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00
:00	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.05	0.05	0.00
:15	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.09	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.00
:30	0.05	0.05	0.05	0.05	0.05	0.05	0.09	0.09	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00
:45	0.05	0.05	0.05	0.05	0.00	0.00	0.09	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.05	0.00	0.00	0.00

Figure B 4: Recurrent bottlenecks on the NC study corridor for Fridays