

Research Article

Operational Evaluation of Part-Time Shoulder Use for Interstate 476 in the State of Pennsylvania

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Part-time shoulder use (PTSU) is a capacity-adding strategy that utilized the shoulder temporarily during the peak commuting period and is used sporadically throughout the United States of America (USA). This strategy aids in addressing a transportation-related issue for major metropolitan areas. Around major metropolitan areas, the land availability is limited due to high population counts, which makes widening roadways for growing populations complex and expensive. Many countries are looking at methods that better utilize the transportation infrastructure currently constructed before widening the roadway. PTSU provides a possible solution to this problem, and this research aims to evaluate the operational benefits of PTSU using a case study based in the state of Pennsylvania. Interstate 476 (I-476), in the Philadelphia, Pennsylvania, metropolitan area is a prime candidate for PTSU. This four-lane highway has peak directional volumes of around 4,700 vehicles per hour in particular sections during the morning commuting period. I-476 is a major commuting route for the region, and the additional capacity during the commuting periods would greatly improve the flow of the surrounding network. This analysis was completed using a Vissim model simulating the 7 AM to 9 AM commuting period. A variety of PTSU scenarios were analyzed including (1) general purpose PTSU lane, (2) passenger cars only PTSU lane, (3) heavy trucks only PTSU lane, and (4) general purpose PTSU lane where additional traffic is induced. Overall, this study determined that PTSU could significantly decrease the travel time on I-476, regardless of vehicle type restrictions, and could provide a more stable traffic density throughout the I-476 network. This research provides additional insight into the effects of vehicle type restrictions on the effectiveness of PTSU and further strengthens the understanding of the operational benefit of PTSU.

1. Introduction

The use of the shoulder as a travel lane is applied mainly in European countries such as the Netherlands, Germany, and the United Kingdom [1]. The extent of PTSU in Europe is expansive with 1000 kilometers in the Netherlands, over 200 kilometers in Germany, and an initial evaluation of 18 kilometers in the United Kingdom, as of 2010 [1]. In the USA, implementations began as bus-on-shoulder (BOS) lanes but have expanded to all types of PTSU in sixteen states with nine of them being at least a general purpose lane of PTSU [2]. Each of these sixteen states implemented PTSU in their unique design to fit the requirements for the highway. Some use simple signage to indicate operating times, and others

combine PTSU with other roadway improvement methods such as high occupancy vehicle (HOV) lanes. Overall PTSU in the USA is predominantly transit based [3]. With the variety of circumstances of transportation infrastructure in the USA, there is a need to further expand the understanding of PTSU in USA applications, especially in localized research. Though the form of PTSU presented in this study is a simple implementation that utilizes existing technologies, results indicated significant benefits. With further improvements in smart cities and connected vehicles, the current literature suggests the dynamic lane management strategies will become increasingly more relevant and effective, making understanding PTSU imperative. [4].

I-476 in Philadelphia, Pennsylvania, is a prime candidate for PTSU implementation. The roadway decreases from

a six-lane highway to a four-lane highway for the southern 14.5 kilometers of the roadway before it splits into Interstate 95 (I-95), shown in Figure 1 in Methodology and Calibration Results. Within the four-lane highway segment, the northbound (NB) hourly volumes range 3,600 to 4,700 vehicles per hour (veh/h) and the southbound (SB) hourly volumes range 2,400 to 4,200 veh/h. Due to these high volumes and the reduced geometric cross section, the Delaware Valley Regional Planning Commission (DVRPC), the regional Metropolitan Planning Organization (MPO) of Greater Philadelphia, has included the implementation of PTSU on this section of highway in the long-range plan [5–7]. The nearest example of a significant implementation of PTSU is in the Washington, District of Columbia area, which is two to three hours south of I-476. This research aims to evaluate possible operational effects of PTSU on I-476 with a Vissim-based model case study [8]. The operational indicators assessed include travel time and lane density when compared to the base model. This research will focus on understanding the operational effects of PTSU as a general lane along with three other PTSU scenarios: passenger car only PTSU, heavy truck only PTSU, and PTSU where the volumes throughout the network significantly increased, a 30% increase, due to the improved operations during the commuting periods when PTSU is open. This research paper aims at addressing the transportation problem of confronting the growing need for higher capacity roadways with limited available land use by utilizing PTSU.

2. Literature Review

The major implementations of PTSU, or known internationally as hard shoulder running (HSR), can be broken down into three types, BOS, static, and dynamic PTSU [2]. BOS PTSU is common around major metropolitan areas where there is significant transit traffic. BOS allows the use of the shoulder for bus travel during specific periods throughout the day to ensure transit reliability. Static PTSU is the use of the shoulder as a travel lane at specific times of the day, typically the primary commuting hours. Static PTSU could include various vehicle type restrictions such as passenger car only lanes, heavy truck only lanes, or HOV lanes [2]. Dynamic PTSU is similar to static PTSU, but the hours of operation are adjustable. Instead of specific hours of operations, the shoulder lanes open when the density of the roadway increases to a site-specific level that would benefit significantly from PTSU. This method is ideal for areas where traffic volumes are highly variable throughout the day such as roadways around major tourist areas where the arrival times to the area are sporadically throughout the day.

As PTSU becomes more prominent in the USA, the operational effects will be further evaluated and understood. Even within the limited applications in the USA, a report by the Federal Highway Administration (FHWA) summarized the capacity potential of PTSU in the USA to range from 1,000 to 2,000 veh/h, which agreed with another USA-based study out of the state of Virginia [2, 9]. The one simulation-based study on a roadway in Buffalo, New York region, evaluated the effects of the length of the PTSU areas (length

of the bottleneck versus the length of the bottleneck along with the upstream queue) and the width of the shoulder lane (3.05 meters versus 3.66 meters) [10]. The shorter and narrower PTSU implementation had a capacity of 1,262 veh/h, while the longer and wider PTSU implementation had a capacity of 1,687 veh/h. Others have found the PTSU lane to be able to handle 1/3 to 1/2 of the mainline traffic volume [2, 11]. Other studies have found the capacity to be around 15 to 20% of the mainline volume, depending on the number of lanes on the highway [11, 12]. The total capacity of a roadway has been found to increase by 7 to 35% by European-based projects [13–15]. The additional capacity created by a third lane on a two-lane segment of a United Kingdom (UK) highway was found to offset the significant negative effects of higher lane volumes on the average vehicle speed until the total segment volume increased by about 75% [16]. A theoretical study based on Interstate 70 (I-70) in the state of Colorado, USA, determined that an additional lane for a two-lane segment of I-70 could reduce the lane density by 33%, assuming no induced volume caused by the improved operational performance [17]. However, a study based in the state of Texas, USA, found that the overall roadway density could reduce up to 70% [18].

The operational performance effect indicators vary depending on the location. An evaluation of PTSU in the state of Washington found that the travel time reduced from nine minutes to one and a half minutes for a 2.49-kilometer segment of PTSU [2]. A United Kingdom study for the M42 motorway found that the variability of the travel time decreased by 27 to 34%, and a France-based study found an over improvement in travel time reliability [19, 20]. Congestion was found to reduce by up to 35% in a German study and congestion frequency to reduce by up to 82% [21, 22]. A study based in Alabama, USA, found that left shoulder PTSU could reduce the total travel time by 0.54 minutes per kilometer and 0.05 minutes per kilometer for right shoulder PTSU [23]. The overall reduction in delay was determined to be 0.25 to 0.62 minutes per kilometer of PTSU implementation, based on two studies [2, 23]. The design can be optimized to minimize total time delay during traffic incidents [24]. An analysis about the density of a highway with shoulder use has found to improve safety due to the overall reduction in the density of the highway [25]. These results highlight the variability of the operational effects of PTSU. This study aims to improve the knowledge of PTSU for the USA implementations.

3. Methodology and Calibration Results

The network analyzed for this study extends 13.4 kilometers from the center of Interchange 9 to the center of Interchange 1 on I-476 as shown in Figure 1. The Vissim model includes 1.6 kilometers north of the center of Interchange 9 and south of Interchange 1 where I-476 splits to merge with I-95 in either direction. There are four total interchanges, Interchanges 1, 3, 5, and 9. The analysis segments are from the center of each interchange to the next interchange. For the NB direction, the analysis segments are between Interchange 1 to 3, Interchange 3 to 5, and Interchange 5 to 9. The SB

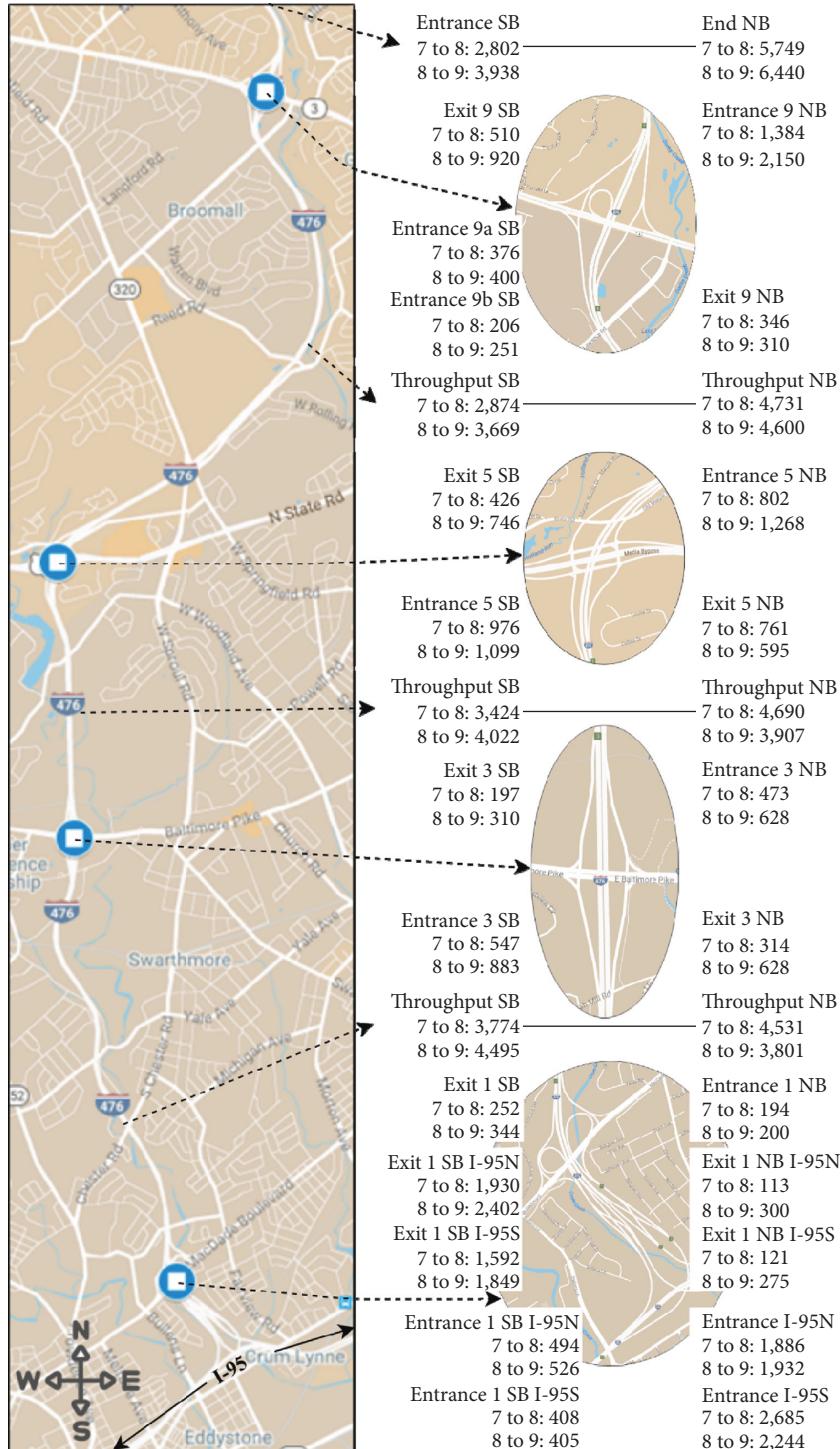


FIGURE 1: Network area map with hourly traffic volumes, veh/h.

direction analysis segments are the same but with the interchanges in the decreasing number. Figure 1 includes a network map of the modeled interstate with the hourly volumes used within the analysis. The analysis period is the two-hour morning commuting period from 7 AM to 9 AM. The NB direction has higher volumes overall though the SB direction has volumes that are comparable in specific segments. The percentage of trucks on I-476 is approximately

10% throughout, and 10% will be used as the network average for the Vissim model. The posted speed limit for I-476 is 55 miles per hour (mph; 88.5 kilometers per hour (km/h)). The model was calibrated using travel times that were collected in autumn 2015 by researchers at Villanova University, shown in Table 1. The model was calibrated using a single seed number where the simulated travel time was found to be not statistically different from the real world

TABLE 1: Calibrated travel time and speed values.

	Measured travel time (min)		Calibrated travel time (min)	
	Southbound	Northbound	Southbound	Northbound
Between interchanges 5 and 9	5.40	5.08	4.75	5.25
Between interchanges 3 and 5	3.72	5.11	3.51	5.40
Between interchanges 1 and 3	3.63	9.48	3.85	8.84
Total	12.74	19.66	11.66	18.23

measured travel times of the analysis segments. Once completed, the variability was assessed using the speed between the interchanges to validate the model by determining if the variability of the model to be less than 10% from the average values measured within the microsimulation based on ten simulation runs using ten random seed values. The speed data were from INRIX data provided by the Regional Integrated Transportation Information System online database, Probe Data Analytics Suite [26]. The model was run for ten simulation runs which were determined to be sufficient to capture the variability of the microsimulation model with 95% confidence and completed the calibration process. The average travel times of the ten randomly seeded simulation runs for each analysis segment is included below in Table 1.

Four PTSU scenarios were analyzed: (1) PTSU as a general purpose lane, (2) PTSU as a passenger car only lane, (3) PTSU as a heavy truck only lane, and (4) PTSU as a general purpose lane with induced traffic. These four scenarios will be referenced in Figures 2–4 as PTSU, passenger car PTSU, heavy truck PTSU, and induced PTSU, respectively. These four scenarios are possible scenarios for I-476 with the implementation of PTSU. BOS PTSU was not included in this analysis as there are no transit routes on this I-476 segment. Hence, BOS PTSU was not relevant for this study. All four of these scenarios are compared to the base scenarios without PTSU using travel time and lane density. Lane density is represented as vehicles per kilometers per lane (veh/km/lane). Density is also compared to the level of service (LOS) that quantifies the quality of the traffic flow based on the lane density for highways [27].

4. Results and Analysis

The benefit of PTSU on the operational performance is evident in the NB performance change from the base I-476 conditions. Figure 2 includes the average travel time along with the 95% confidence interval of the base scenario and the aforementioned PTSU scenarios. The variability of the scenarios is relatively minimal. The highest variability is in the SB segment, Interchange 3 to 1, where the segment ends in a split of I-476 with one direction exiting onto I-95 SB and the other onto I-95 NB. Interchange 1 SB has high levels of lane changing that can cause inconsistent travel times at the end of this analysis segment. The SB direction only saw a significant reduction between Interchanges 5 and 3 where the reduction is around 43%. The other SB segments saw a reduction of zero to 15% when compared to the base scenario. Due to geometric limitations of one of the I-95

ramps, with the induced PTSU scenario, there is a significant increase in travel time between Interchanges 3 and 1 and a minimal increase between Interchanges 5 and 3. Without this geometric limitation, the performance for the SB direction with the induced PTSU scenario is expected to be similar to the induced PTSU in the NB direction, lower or similar to the base scenario travel time values. For the other NB PTSU scenarios, the reduction is over 60% between Interchanges 1 and 5. From Interchange 5 to 9, the speed of the traffic was near the posted speed limit in the base scenario, and with PTSU, the travel time reduced by about 23% from the base scenario. Between all of the analysis segments, there is minimal difference between the noninduced PTSU scenarios in average travel time in both directions. The most variable is between Interchanges 3 and 1 SB where the need for lane changing is higher for trucks in the PTSU lane which caused an increase in travel time. However, the other noninduced PTSU scenarios were statistically similar to each other in the SB Interchange 3 to 1 segment.

The density of the NB segments depicted in Figure 3 illustrates how the overall congestion forms within the network. In the base conditions, the congestion begins between Interchanges 3 and 5 before it extends into the Interchange 1 to 3 segment. The highest volumes are between Interchanges 5 and 9, but the end of that segment introduces a new lane, and it is the longest segment of I-476 in the analysis network without a ramp. These two factors allow for better operations between Interchanges 5 and 9 where the density stabilizes at the border between LOS D and LOS E. This allows for sporadic areas of congestion to form due to unstable flow but not a complete breakdown of the traffic flow like the other NB segments. The other two NB base scenario segments achieve a LOS of F within the first 30 minutes of the two-hour congestion period. With PTSU, the density drops to around sixteen vehicles per kilometer per lane where the LOS of I-476 is between LOS C and LOS D. For the induced PTSU scenario, the density between Interchanges 3 and 5 increases similarly to the base scenario, but it levels off for the rest of the two-hour commuting period. The level off in density for the Interchange 3 to 5 segment allows for the density for the Interchange 1 to 3 segment to peak and decrease in the second hour of the analysis periods where the traffic volumes decrease. While the Interchange 3 to 5 segment operates at a LOS F, the PTSU minimized the increased LOS F density of the Interchange 1 to 3 segment to be maintained for only an hour instead of the base scenario of an hour and a half.

The SB direction has less congestion which results in the density over time profile for the SB direction to be simpler

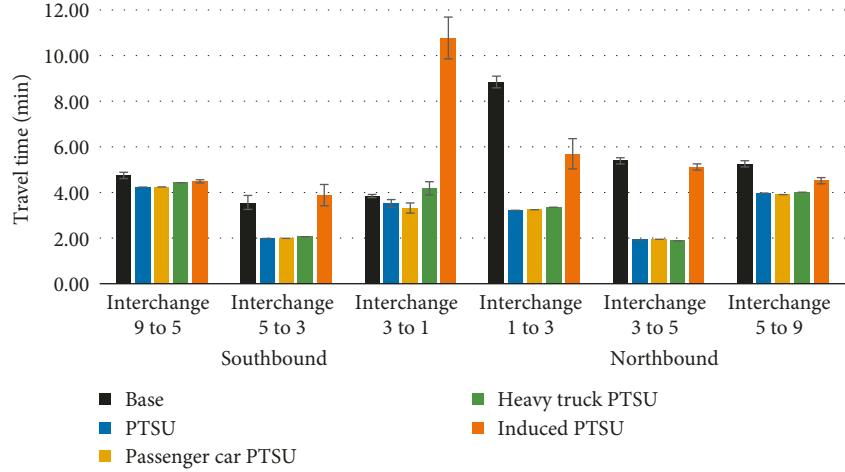


FIGURE 2: Travel time comparison of the base scenario to PTSU scenarios.

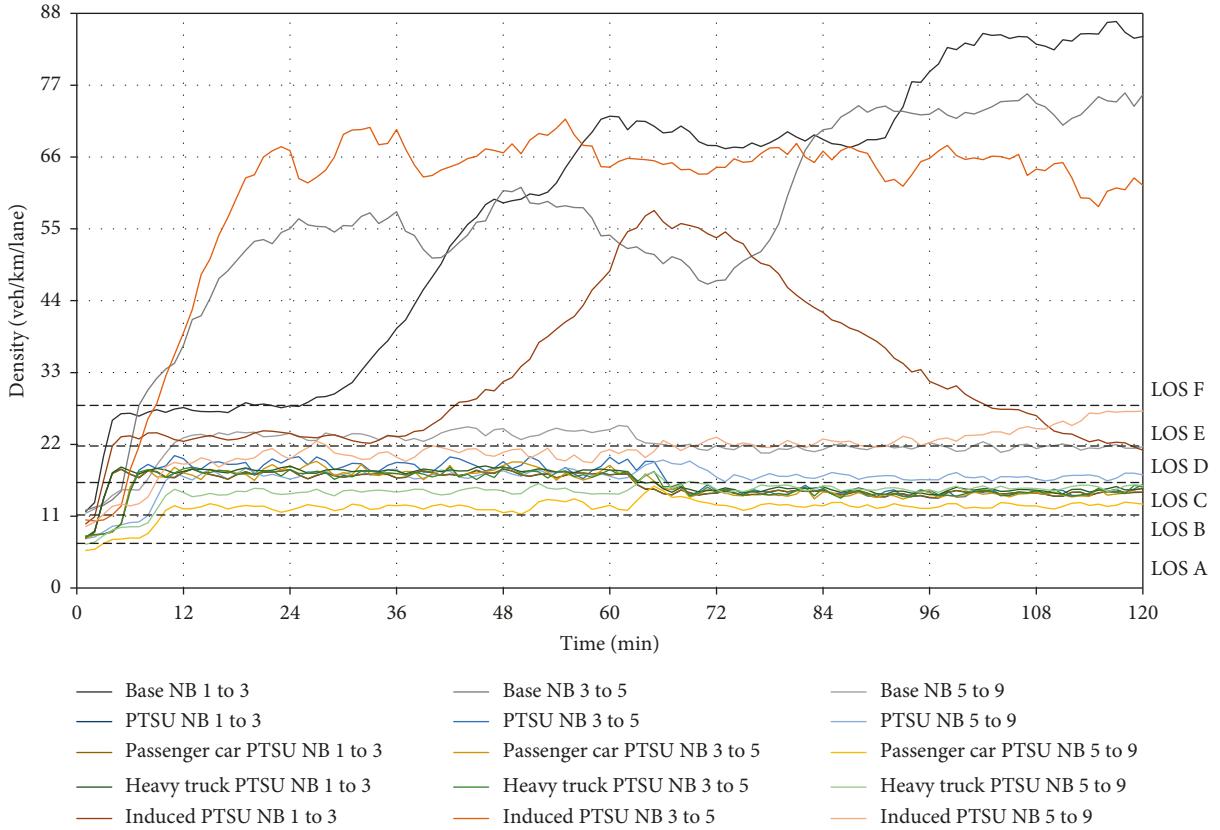


FIGURE 3: NB lane density by analysis segment.

than the NB direction, shown in Figure 4. In the base conditions, the density increases to just above a LOS C in the second hour of the analysis period. In the induced PTSU scenario, due to the geometric issue mentioned, the density begins to increase around 30 minutes into the two-hour analysis period for the Interchange 3 to 1 segment. The Interchange 3 to 1 segment eventually levels off at around 80 minutes into the analysis period when Interchange 5 to 3 segment begins to increase as the congestion extends into

that segment. The noninduced PTSU scenarios operate around LOS B except for the last half hour of the analysis period. Due to the higher volumes in the second hour for the SB direction, the density between Interchanges 3 and 1 begins to increase, but in the worst case scenario, the truck PTSU scenario, only reached LOS F at the end of the two-hour analysis period. The general PTSU and passenger car PTSU only reach a LOS of D by the end of the analysis period.

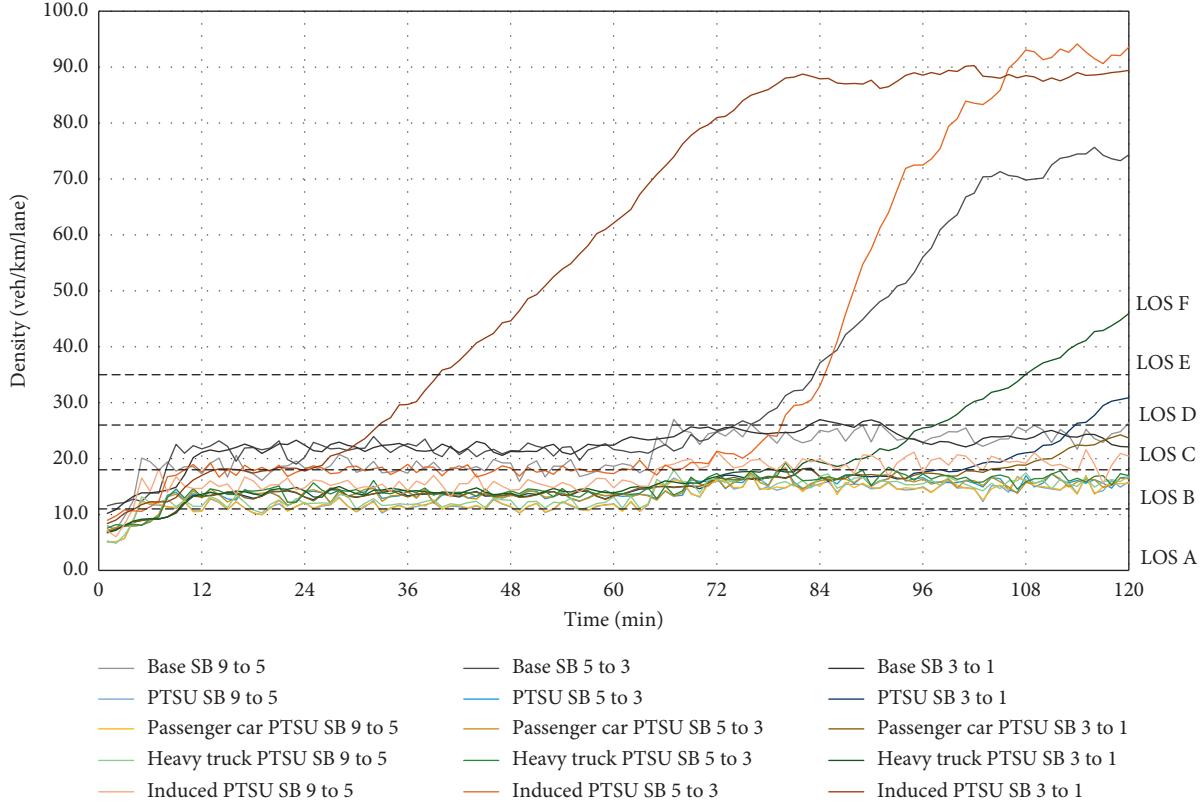


FIGURE 4: SB lane density by analysis segment.

The travel time reductions found in this paper are approximately 0.00 to 1.86 minutes per kilometer. This expanded the overall range determined in the literature, 0.05 to 0.62 minutes per kilometer [2, 23]. The two most congested segments have a travel time reduction range of 1.08 to 1.86 minutes per kilometer. The higher initial levels of congestion presented an ideal scenario for increased travel time reductions. The travel time reductions in the other analysis segments fell within the range determined in the literature review section [2, 23]. Similar to the travel time reductions, the two most congestion segments of I-476, between Interchange 1 and Interchange 5 NB, have lane density reductions higher than the range determined in the literature [17, 18]. However, the increased density reductions found in this study are only slightly higher than the literature upper limit for roadway density reduction. The less congested segments had lane density reductions similar to the lower limits of the literature review range. The results of this study fit within the current body of knowledge of PTSU. However, it does provide additional detail on the variability of the operational benefit of PTSU over time and location.

5. Conclusions

The objective of this study was to understand the operational effects of PTSU. The addition of a lane during the two-hour morning commuting period provided significant improvement to the travel time. The NB direction had higher levels of congestion, so the benefit was predominantly in the NB

direction. However, the SB direction did have significant travel time reduction in the one analysis segment with higher levels of congestion in the base conditions. The use of PTSU had a significant effect on the lane density throughout both directions. Instead of segments of I-476 becoming unstable during the morning commuting period, the traffic flow remained relatively stable. With the higher volumes in the NB direction, the traffic flow is not going to be perfectly stable as it was on the border between LOS C and D. However, the traffic density will be less variable over time than the base scenarios where the density is increasing throughout the two-hour analysis period. Based on the conditions in this model, the optimal PTSU scenario was the passenger cars only PTSU scenario. Trucks in the PTSU lane adds merging issues at interchanges and lane changing issues at interchanges such as Interchange 1 SB where there is a major roadway split. Depending on the truck volume on a roadway, the effects of the trucks will vary. PTSU is a unique solution that utilizes the existing roadway more efficiently and provides a stable roadway that operates at a faster speed.

From this study, the following key points can be applied to other PTSU scenarios. The improved operational performance, created by PTSU, may induce traffic. Understanding the geometric limitations of the roadway segment can be a significant impact on the effectiveness of the implementation, as any current limitations will likely be exacerbated with PTSU. If possible, it is recommended to use the left shoulder as the literature suggests that the left

shoulder PTSU can be more beneficial than right shoulder PTSU [22]. Also, the vehicle composition of the roadway could be a determining factor if vehicle type restrictions are necessary for any future PTSU implementation such as the quantity of heavy vehicles impacting the shoulder pavement performance. One last key point that could influence the PTSU implementation is the extent of the area that could benefit from PTSU. For example, if PTSU is only needed between two interchanges, extending PTSU further could reduce the cost-effectiveness of the implementation. However, in cases where PTSU is not extended far enough along the roadway segment, the operational benefit may be minimized by significant pockets of congestion still existing along the roadway segment. These key points can aid in increasing the overall effectiveness of PTSU in other scenario applications.

6. Future Work

This study focused on ideal conditions where no incidents are present. Future work will evaluate the effects of PTSU in crash-based scenarios that obstruct one of the lanes during the entire commuting period. Blocking the lane for the entire commuting period will provide a worst case scenario for a crash-based scenario but will add insight to the effects of PTSU in crash mitigation during the peak commuting period. The inclusion of crash-based scenarios will strengthen the understanding of PTSU operation effects by evaluating PTSU functionality in nonideal operating scenarios.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors have no conflicts of interest regarding the research presented in this paper.

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