Effectiveness of Transit Signal Priority Strategies at Intersections with High Truck Volumes

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

This thesis discusses the effectiveness of two Transit Signal Priority (TSP) strategies, Queue Jump Lane combined with Advanced Transit Signal (QJL-TS) and Green Extension (GE), at an isolated intersection during near-saturated and over-saturated traffic conditions. Each of these scenarios were tested under various conditions using a mix of variables including bus headways of 5, 10, and 15 minutes as well as truck composition consisting of 5%, 10%, 15%, and 20% heavy trucks. The study also considers the location of bus stops by analyzing both near side and far side stops. The analysis is undertaken using Synchro software to determine optimal signal timing plans and PTV-VISSIM software to analyze average vehicle delay at the intersection.

The study concluded that higher truck percentage leads to higher delay experienced by all vehicles at the intersection. It was also observed that vehicles experienced a higher delay during over-saturated conditions as expected. It was also noted that for both the near-saturated and over-saturated traffic conditions, GE provides higher benefit compared to QJL-TS, with the highest benefit observed in the scenarios with lower truck percentages traffic composition, i.e. 5% truck percentage.

Acknowledgements

I would like to express my deepest appreciation to my supervisor, Dr. Liping Fu, who has provided me with this opportunity and who has helped in the development of this research. Dr. Fu's advice has been invaluable and this thesis would not have been possible without his support.

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Last but not least, I would like to thank my partner Miloš, you truly are my inspiration and this would not have been possible without your support.

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1. Introduction

1.1 Background

"An advanced city is not one where even the poor use cars, but rather one where even the rich use public transport." - Former Bogotá Mayor, Enrique Peñalosa

Public transit plays a vital role in shaping Canadian communities and the way the inhabitants of these communities move around. The evolution of public transit in Canada, as in other places in the world, has been long and challenging with public and private agencies still striving to provide a safe, affordable, accessible, and competitive system that can thrive in today's automobile-dominated era. Not only is public transit crucial in providing equity among the citizens of a city, but it also has a significant impact on a community's economic development by encouraging employment, business activity, and property values among other benefits.

Buses, one of the main and most common transit service vehicles currently in operation, are constantly competing for quality of service and specifically reliability, which has been a major factor in the popularity of buses and transit in general. In order to improve quality of service and reliability, transit has always had to better compete with other modes of transportation, such as cars, which normally tend to have an advantage by being more accessible, faster, and a more convenient mode of travel.

One method of improving the quality of service of buses is by reducing their delay, specifically control delay, at signalized intersections. Control delay is defined as the delay brought about by the presence of a traffic control device (HCM 2016). It includes delay when vehicles slow in advance of an intersection, time spent stopped on an intersection approach, time spent as vehicles move up in the queue, and time needed for vehicles to accelerate to their desired speed (HCM 2016). Transit priority is one of the popular methods used by government agencies to reduce transit delays at signalized intersections. The *Advanced Traffic Management Systems Committee and Advanced Public Transportation Systems Committee of the Intelligent Transportation Society of America* define Transit Signal Priority (TSP) as an operational strategy that facilitates the movement of in-service transit vehicles, either buses or streetcars, through traffic-signal controlled intersections. TSPs provide the potential for reducing per-person delay at intersections, thus improving travel time for a higher number of road users. Unlike preemption, used for emergency vehicles which tend to interrupt the normal process of signal operations, TSPs modify normal signal operation process to better accommodate transit vehicles (Figure 1) (ITS America, 2004).

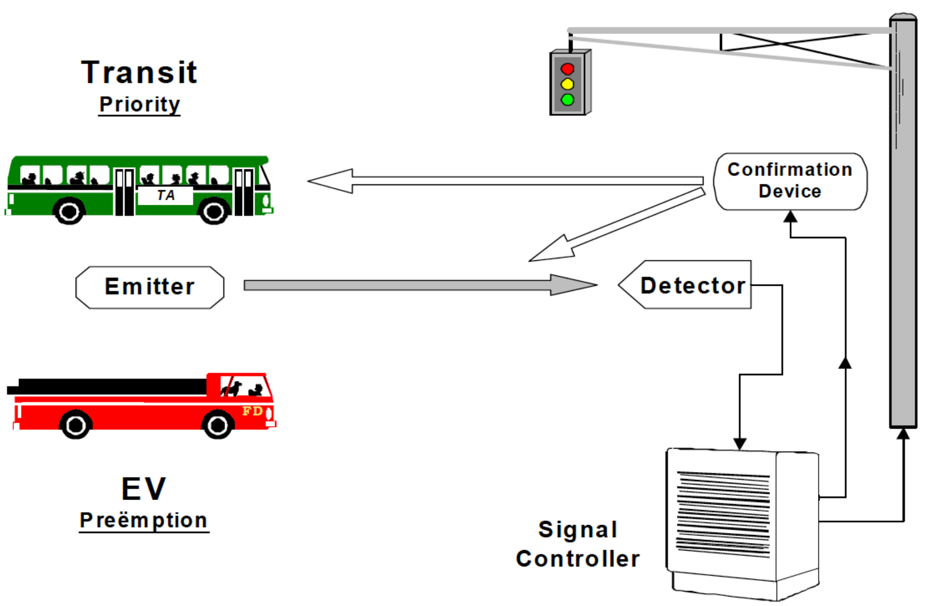


Figure 1 Priority vs Preemption (ITS America, 2004)

There are two types of transit priority, namely passive and active priorities. Passive priority includes strategies such as coordinating signals along a corridor and can operate regardless of whether transit is present or not. Active priority requires the detection of a transit vehicle using infrastructure such as detectors and providing the transit vehicles with special treatments (FTA, 2016) such as phase rotation, phase insertion, green extension, red truncation, or phase skipping.

Another popular TSP scheme is called queue jump (Figure 2), which consists of a combination of a short lane with a leading transit signal phase interval to allow buses to bypass the traffic queue. This scheme is sometimes used in combination with TSPs or as stand-alone alternative to reduce transit delays at intersections. A right-turn bay, consisting of a nearside right-turn only lane, and a far-side open bus bay, is sometimes used if present.

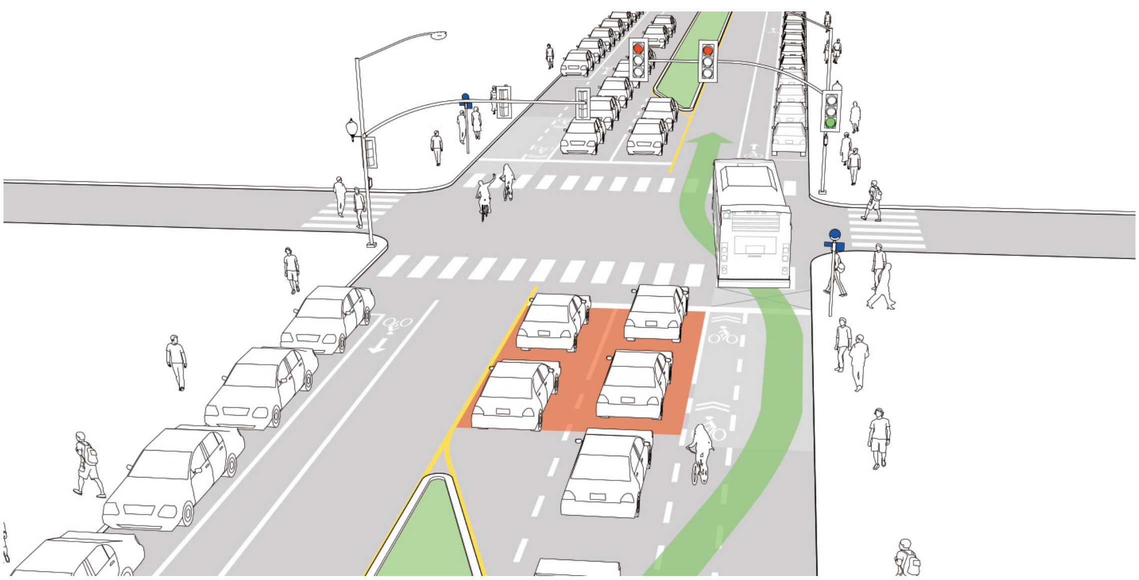


Figure 2 Queue Jump Lane (NACTO, 2019)

There are many factors that may influence the effectiveness of TSPs. Some of these factors include saturation levels, noting that TSPs have been shown to be ineffective during saturated conditions (Ngan, Sayed, and Abdelfatah, 2004) as buses are not able to bypass the long waiting queues at intersections. Other factors include geometric configuration of the intersection, location of the bus stop, and bus headway (Rakha and Zhang, 2004). Another potential factor is the traffic composition, especially, percentage of trucks. In his paper, *Too Many Trucks on the Road?,* Baldwin (2005) states that although the number of trucks registered are fewer than registered cars, trucks seem to have become more visible on Canadian Roads. “Trucks are more ‘visible’ on the road not just because they are bigger. They also travel longer distances than cars, increasing the likelihood to encounter them on the road.” He notes that a large truck, although less than a small truck, is also more likely to be seen on roads due to higher vehicle-kilometers driven as shown in Table 1 (Baldwin, 2005).

Table 1 Vehicle-kilometers driven, by vehicle type (Baldwin, 2005)

Vehicle-kilometres driven, by vehicle type, Canada, 2003

Vehicle type	Total	Annual average	Daily average
	billions of vehicle-km	km per vehicle	
Small trucks	6.2	19 144	52
Large trucks	18.6	66 640	183
Cars	286.3	16 333	45

Source: Statistics Canada, *Canadian Vehicle Survey, Annual 2003*, Catalogue no. 53-223-XIE, pages 26 and 30.

The high number of trucks are especially important at intersections where the impact of trucks are high when a significant percentage of trucks are present (Washburn and Cruz-Casas, 2010). These trucks, therefore, have a high impact not only on car traffic but transit vehicles as well. As trucks tend to have unique characteristics, such as lower acceleration and deceleration rates, they tend to greatly affect the conditions on the road, including their impact on transit delay. However, little is known about the magnitude of these impacts, how they differ under different conditions and with different TSP, and how the impact of trucks can be minimized. As there has been little research done on the impact of the truck volumes on transit delay and the effectiveness of TSP, this study aims at quantifying the impacts of truck volumes on various TSP strategies under a wide range of traffic conditions and bus service frequencies.

1.2 Research Objectives

In order to better understand the impacts of truck behaviors, the objective of this study is to analyze the impact of truck percentages on bus delay at signalized intersections. The study aims at answering the following questions:

- What is the effect of truck traffic on the effectiveness of various TSP (Queue Jump Lanes – Phase Insertion and Green Extensions)?
- What are the related factors that influence the interaction between truck traffic and transit buses?
- What are the impacts of truck percentages under various conditions such as intersection volume/ capacity ratio and transit headway?

1.3 Thesis Structure

Section 2 introduces and summarizes previous studies and research. It is divided into three parts, namely Types of TSP Strategies, Impacts of TSP Strategies and Characteristics, Impacts and Simulation of Heavy Vehicles.

Section 3 describes the research methodology including the transportations models used in the study, the coding of the network and model input parameters. The section also introduces a preliminary analysis along with various scenarios that were tested during this study.

Section 4 summarizes the results of the study along with noted observations, while section 5 states the conclusions of the analysis and recommendations for future research.

2. Literature Review

This chapter summarizes previous studies and research on impacts and effectiveness of TSPs and Queue Jump lanes referring to both field and microsimulation analysis, the characteristics of heavy vehicles and their impact on intersection delay, and model parameters applied during studies involving TSPs and heavy vehicles.

2.1 Types of TSP Strategies

2.1.1 Passive Priority Strategies

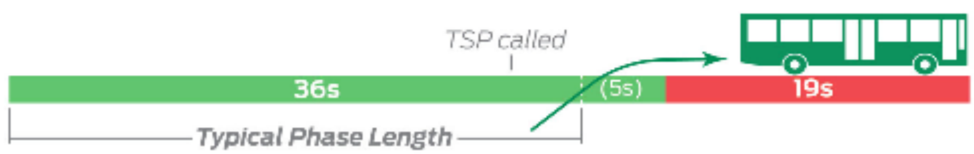
As discussed in section 1.1, passive priority includes strategies such as coordinating signals along a corridor and can operate regardless of whether transit is present or not. It uses static signal settings, such as allocating more green time to the street with the transit route, to reduce delay for transit. The following is a list of some commonly used passive strategies:

- Shorter Cycle Length: This strategy reduces delay by shortening the wait time until the next green phase. The short cycle length, however, increase lost time and thus reduces intersection capacity.
- Split Phasing: This strategy splits the green phase for the transit into two within the same cycle. It also tends to increase lost time, however, the increase is potentially less than the "Shorter Cycle Length" strategy.
- Signal coordination: This strategy enables arterial progression, by ensuring that transit vehicles arrive at the green phase.

2.1.2 Active Priority Strategies

Active strategies alter signal timing settings, thus minimizing delay to an approaching transit vehicle. The following is a list of some commonly used active strategies (NACTO, 2019):

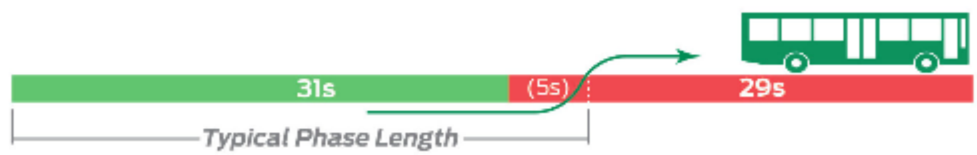
- Green Extension: This strategy provides additional time for the detected transit vehicle to pass through an intersection. Green extension is beneficial in cases when transit runs at the back of the vehicle queue and is the simplest TSP to implement on urban streets.



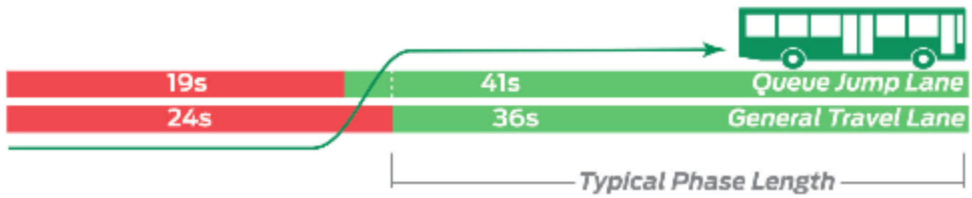
- Green Reallocation: This strategy shifts the green phase depending on the arrival time of transit vehicles. The green phase begins and ends late to accommodate transit. Phase reallocation tends to provide similar benefits to phase extension, however, the impact to cross street traffic is less as the total green time per cycle does not change.

- Red Truncation: This strategy provides a green phase earlier than programmed by reducing the all red phase. It should be noted that the red truncation strategy is beneficial when transit vehicles are detected far enough for the crossing pedestrian phase to clear.

- Upstream Green Truncation: This strategy, also known as a reverse queue jump, stops traffic behind a bus as boarding is completed, allowing the bus to re-enter the lane after a pull-out stop. Green truncation is most effective on moderate frequency transit routes where delay upon reentry due to congestion is common and can also benefit passengers alighting and crossing the street behind the bus.



- Phase Insertions and Phase Sequence Changes: This strategy includes special bus-only phases or prioritization of turn phases used for shared turn/queue jump lanes.



- Phase Reservicing: This strategy provides the same phase twice in a given signal cycle Phase reservicing can potentially significantly reduce transit delay, especially in scenarios when the phase is relatively short.

2.2 Impacts of TSP Strategies

Garrow and Machemehl (1999) used TRAF-Netsim simulation program to analyze the various impacts of TSP strategizes along an arterial corridor. The study concluded that TSPs tend to have significant impact on cross streets with saturation level of 0.9 and higher and should be avoided in those scenarios. The study also concluded that a near-side bus stop vs a far-side bus stop greatly hinders the effectiveness of green extensions and that transit signal priority is more successful when used with far-side bus stops, rather than with near-side bus stops. As shown in Table 2 below, the study also concluded that for an isolated intersection, a 10-second Green Extension was preferred over a 20-second Green Extension, showing that larger green extensions affect the original timing further.

Table 2 Travel Time per Person (seconds/person) at 38th Street and Guadalupe (Garrow and Machemehl, 1999)

10-Second Green Extension	Priority	Base Case	% Change from Base
Bus approach saturation level = 0.8	47.5	47.6	-0.2
Bus approach saturation level = 0.9	49.1	49.9	-1.7
Bus approach saturation level = 1.0	53.0	55.0	-3.7
20-Second Green Extension			
Bus approach saturation level = 0.8	52.8	49.8	6.1
Bus approach saturation level = 0.9	52.7	50.8	3.7
Bus approach saturation level = 1.0	55.3	56.6	-2.3

(Auto Occupancy =1.2, Bus Occupancy = 25)

Wolput et al. (2015) examined the effectiveness for 24 transit and traffic demand scenarios of 12 different active TSP strategy algorithms. The researchers used a combination of CAPACITEL mesomodel and VISSIM microsimulation model for an isolated intersection. The 12 different active TSP strategies combination are shown in Table 3 below:

Table 3 TSP Strategies (Wolput et al., 2015)

Active TSP Strategy	No Green Extension or Red Truncation	Green Extension	Green Extension and Red Truncation
Fixed Phase Sequence	Yes	Yes	Yes
Phase Insertion	Yes	Yes	Yes
Phase Rotation	Yes	Yes	Yes
Phase Skipping	Yes	Yes	Yes

The analysis was undertaken under various traffic (under-saturated, near-saturated, and oversaturated intersection flow ratios) and transit demand scenarios (flow ratio of transit, frequency, and frequency of conflicting bus lines). Red truncation has been mathematically shown to always perform worse compared to green extension for both scenarios and was, therefore, excluded from the analysis. Average person delay and improving travel time reliability (minimal standard deviation of person delay) compared to a No TSP scenario was used a measure of effectiveness in this study. The study concluded that person per vehicle occupancy weights for buses and cars do not impact signal timings significantly, however, they influence average weighted delay and performance of a TSP. The researchers, therefore, decided that an occupancy weight of 30 for buses and 1.2 for cars was reasonable for their analysis. The study further concluded that during under-saturated conditions any TSP (except for phase skipping) is optimal, in near-saturated conditions, green extension, phase insertion, phase insertion with green extension and phase rotation with green extension perform better than No TSP, and in oversaturated conditions, only green extension can compete with No TSP, while phase insertion, phase insertion with green extension and phase rotation with green extension, can still be used with limited additional negative effects.

Skabardonis and Christofa (2011) analyzes a macroscopic procedure to measure the impacts of TSP strategies on control delay and Level of Service (LOS) at each approach and the whole intersection by modifying the Highway Capacity Manual (HCM) formula. The paper acknowledges the use of microsimulation and field tests in previous studies but notes that these procedures are timely and costly. The researchers also note that previous analytical methods have ignored random and oversaturation delays, and therefore do not accurately estimate the impact of oversaturated non-priority approaches.

The impacts on cross street traffic were evaluated for several cycle lengths (C) and green time to cycle length ratios (g/C). The conditions set for the analysis included an initial scenario flow ratio (v/s) of 0.33, green time extension for the main street by 5 seconds, and extension of the green time for the main street by 10 seconds. The overall results are as follows:

- Longer cycle lengths result in lower impacts of the TSP strategies on cross street traffic;
- Higher green time to cycle length ratio result in lower impact of the TSP strategies on cross street traffic;
- Higher reductions in the green time of the cross-street (i.e., longer extension or truncation intervals) increases the impact.

The impact on the LOS of a cross-street for a 5 second provision of TSP (green extension or red truncation) to buses traveling on the main street with a frequency of 6 buses per hour resulted in LOS for the non-priority cross street on the average remains the same for initial LOS A, B, C or D but leads to higher level of service for initial LOS E.

The impact on the LOS of a cross-street for a 10 second provision of TSP (green extension or red truncation) to buses traveling on the main street with a frequency of 6 buses per hour resulted in the following conclusions:

- LOS for the non-priority cross street remains the same with initial LOS A or B;
- For initial LOS C and D, provision of priority to bus traveling on the main street can lead to much higher delays for the cross-street and can deteriorate their LOS by one/ two levels

Rakha and Zhang (2004) The researchers analyze the impacts of various traffic, transit, and signal timing factors on the potential benefits of TSP. The study uses INTEGRATION software which detects transit vehicles that are within 100 m of the traffic signal to provide either a green extension (5 seconds) or an early green recall (red truncation) to accommodate the approaching transit vehicle, subject to the need to maintain a common network cycle length. The conclusions are based on measures of effectiveness (MOEs) such as average delay, average vehicle stops, and average fuel consumption which are conducted during 80 simulation runs.

Table 4 Study Parametres (Rakha and Zhang, 2004)

Variable	Variable Description	Level Description
A	Bus departure time	0.0, 7.5, 15.0, 22.5, 30.0, 37.5, 45.0, and 52.5
B	Phase scheme	2-phase and 4-phase
C	Total traffic demand	800, 1000, 1200, 1400, and 1600 veh/h
D	Demand distribution	100/1100, 200/1000, 300/900, 400/800, 500/700, 600/600, 700/500, 800/400, 900/300, 1000/200, and 1100/100
E	Cycle length	40, 60, and 80 seconds
F	Phase split	30/70, 40/60, 50/50, 60/40, and 70/30
G	Bus approach	Eastbound and northbound
H	Bus stop duration	5, 10, 15, 30, and 60 seconds
I	Bus frequency	12, 30, and 60 buses/h

The study concluded that benefits of TSP highly depend on several factors such as time of arrival of the transit vehicle within the cycle length, the phase of the traffic signal that is requesting priority, frequency of transit vehicles, demand distribution at a signalized intersection, transit vehicle dwell times at near-side bus stops.

Zlatkovic and Stevanovic (2012) analyzed the effectiveness of queue jump lanes at saturated intersections where transit preferential treatments, such as TSP strategies, are not as effective. The researchers evaluated individual and combined effects of Queue Jumpers (QJ) and Transit Signal Priority (TSP) on performance of a Bus Rapid Transit (BRT) system and vehicular traffic on an Arterial in Utah.

The analysis included 15-minute-headway for BRT buses, 10 seconds of extra time (either for green extension or for red truncation) for transit, and was tested during Level of Service conditions of C and D. The study concluded that the implementation of TSP-only showed slightly better performance for BRT than QJ-only, TSP-only scenario had the smallest impact on cross-street traffic, while the impacts were highest in QJ & TSP scenario, and that the greatest benefits for BRT are observed in the combined QJ & TSP scenario, where the BRT travel times were reduced by 13-22%.

Other similar studies such as a study undertaken by Hunter-Zaworski et al. (1994) resulted in reduction of bus travel time and bus person delay was 5 - 8% and King County DoT that analyzed green extension and early green strategies at twenty intersections along Rainer Avenue in Seattle, observed results of 5-8% reduction in travel times and 25-34% reduction in average intersection bus delay.

Nowlin and Fitzpatrick (1997) performed both field and simulation studies of Queue Jumpers performance, and concluded that Queue Jumpers work well in under-saturated traffic conditions. However, when the through traffic volume exceeded 1,000 vehicles/hour/lane (near saturation), the benefit of Queue Jumpers began to decrease quickly. Lahon (2011) analyzed TSP and Queue Jumpers and concluded that it reduced bus travel times by 30%, without heavily affecting vehicular traffic. The study also showed that intersections with higher v/c ratios for corresponding through movement offer higher travel time savings for the bus when the intersection has TSP and/or Queue Jumpers.

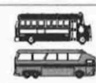
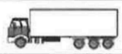
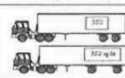
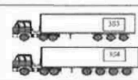
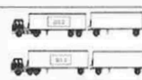
Zhou and Gan (2005) evaluated the impacts of various parameters on Queue Jumpers and green extension and early green strategies in Portland, for thirteen signalized intersections. The evaluations were performed under different TSP strategies, traffic volumes, bus volumes, dwell times, and bus stop and detector locations. It was found that Queue Jumpers without TSP were ineffective in reducing bus delay, as opposed to including TSP strategies such as phase insertion, green extension, red truncation, and phase skipping. Bus travel time savings varied between 2% and 14% per trip, with a two to thirteen seconds reduction in average intersection delays. Nearside bus stops upstream of the check-in detectors were preferred for jumper TSP over far-side bus stops and nearside bus stops downstream of the check-in detectors. The optimal detector location was found to be about 500 feet before the stop line. Through vehicles on the bus approach were found to have only a slight impact on bus delay when the v/c ratio was below 0.9. However, when v/c exceeded 0.9, the bus delay increased quickly. Right turn volumes did not have impacts on bus performance.

2.3 Characteristics, Impact and Simulation Modelling of Heavy Vehicles

The Highway Capacity Manual (HCM) (2016) classifies light and heavy trucks as motorized vehicles modes for analysis. The manual, however, acknowledges that trucks require more roadway space than passenger cars and tend to accelerate more slowly, particularly on upgrades. In order to accounts for these characteristics, therefore, in some cases, trucks are converted into passenger car equivalents or adjusted parameters are used to reflect the specific mix of vehicles in the traffic.

HCM also recognizes trucks as a subclass of heavy vehicles. Heavy vehicles are defined as any vehicle with more than four tires touching the ground, regardless of the number of axles. As the lengths, acceleration characteristics, and deceleration (braking) characteristics of trucks are different from those of passenger cars, The Federal Highway Administration (FHWA) provides a classification of heavy vehicles as shown in the table below followed by average truck acceleration rate (Table 5 and Table 6):

Table 5 FHWA Vehicle Classification Scheme (HCM 2016)

Class	Illustration	Description
1		***Motorcycles.*** All two- or three-wheeled motorized vehicles.
2		***Passenger Cars.*** All sedans, coupes, and station wagons manufactured primarily for carrying passengers and including passenger cars pulling recreational or other light trailers.
3		***Other Two-Axle, Four-Tire Single-Unit Vehicles.*** All two-axle, four-tire vehicles, other than passenger cars. Generally pickup trucks, sport-utility vehicles, and vans.
4		***Buses.*** All vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. Excludes modified buses no longer capable of mass passenger transport.
5		***Two-Axle, Six-Tire Single-Unit Trucks.*** All vehicles on a single frame with two axles and dual rear wheels. Includes some trucks, camping and recreational vehicles, and motor homes.
6		***Three-Axle Single-Unit Trucks.*** All vehicles on a single frame with three axles. Includes some trucks, camping and recreational vehicles, and motor homes.
7		***Four or More Axle Single-Unit Trucks.*** All trucks on a single frame with four or more axles.
8		***Four or Fewer Axle Single-Trailer Trucks.*** All vehicles with four or fewer axles consisting of two units, one of which is a tractor or straight truck power unit.
9		***Five-Axle Single-Trailer* Trucks.** All five-axle vehicles consisting of two units, one of which is a tractor or straight truck power unit.
10		***Six or More Axle Single-Trailer Trucks.*** All vehicles with six or more axles consisting of two units, one of which is a tractor or straight truck power unit.
11		***Five or Fewer Axle Multitrailer Trucks.*** All vehicles with five or fewer axles consisting of three or more units, one of which is a tractor or straight truck power unit.
12		***Six-Axle Multitrailer Trucks.*** All six-axle vehicles consisting of three or more units, one of which is a tractor or straight truck power unit.
13		***Seven or More Axle Multitrailer Trucks.*** All vehicles with seven or more axles consisting of three or more units, one of which is a tractor or straight truck power unit. Includes triple-trailer combinations.

Sources: Adapted from FHWA (*12*) and Maryland State Highway Administration (*13*).
Note: FHWA Classes 1–3 are HCM passenger cars, Class 4 is HCM buses, and Classes 5–13 are HCM trucks.

Table 6 Average Truck Acceleration Rate (ft/s^2) to 40 mi/h (64km/h) (HCM 2016)

Weight-to-Power Ratio (lb/hp)	Starting Speed (mi/h) 0	10	20	30
100	1.87	1.70	1.47	1.29
200	1.22	1.08	0.96	0.79
300	0.91	0.81	0.72	0.58
400	0.71	0.61	0.50	0.36

Source: Harwood et al. (*15*).

HCM also notes that buses stopping in the travel lane on urban streets to serve passengers have a higher effect on trucks compared to automobiles as a result of trucks' poorer acceleration capabilities and the larger gap in traffic that is required for trucks to change lanes to pass the bus. It is also stated that in locations where buses pull out of the travel lane to serve bus stops and where yield-to-bus laws are not in place or observed, buses experience delay waiting for a gap to pull back into traffic after serving a stop (HCM 2016).

HCM 2016 also states that the default bus acceleration rate was changed to 3.3 ft/s^2 (1.01 m/s^2) from 4.0 ft/s^2 (1.22 m/s^2) as part of the update from HCM 2010.

ITE Traffic Engineering Handbook includes acceleration rates for both passenger cars and tractor-semitrailer combination trucks on zero-grade roads as shown in the Table 7 below.

Table 7 Truck Acceleration Rates (ITE Traffic Engineering Handbook)

Vehicle type	Weight-to-power ratio (lb/hp)	Typical maximum acceleration rate on level road (ft/s^2)				
		0–10 mph	0–20 mph	0–30 mph	0–40 mph	0–50 mph
a. Maximum acceleration from standing start						
Tractor-semitrailer	100	2.9	2.3	2.2	2.0	1.6
	200	1.8	1.6	1.5	1.2	1.0
	300	1.3	1.3	1.2	1.1	0.6
	400	1.3	1.2	1.1	0.7	NA

Vehicle type	Weight-to-power ratio (lb/hp)	Typical maximum acceleration rate on level road (ft/s^2)			
		20–30 mph	30–40 mph	40–50 mph	50–60 mph
b. Maximum Acceleration for 10 mph Increments					
Tractor-semitrailer	100	2.1	1.5	1.0	0.6
	200	1.3	0.8	0.5	0.4
	300	1.0	0.6	0.3	NA
	400	0.9	0.4	NA	NA

Washburn and Cruz-Casas (2010) note that the presence of large trucks in the traffic stream are currently being underestimated using the HCM method that includes a Passenger Car

Equivalency (PCE) value of 2.0 is applied for all trucks. The study notes that HCM does not distinguish between different sizes of trucks and also recommends a single value of 2.0 seconds for startup lost time, regardless of queue position of the truck. The PCE values determined from this study are 1.8, 2.2, and 2.8 for small, medium, and large trucks, respectively.

The study cites other papers such as Molina, 1987 which concluded that truck position in a queue does not have a high impact when two- and three-axle single-unit trucks are present, however, the queue position is important with five or more axle combination trucks.

The study classifies heavy vehicles into the following three categories:

- Small trucks: include heavy vehicles with only two axles and between four and six tires.
- Medium trucks: include those trucks with three axles and usually range in length from 40 to 55 ft.
- Large trucks: include those trucks with four or more axles and those longer than 55 ft.

Each of the three categories were included in a microsimulation analysis which concluded in following calibrated parameters.

Table 8 Simulation Calibration Values (Washburn and Cruz-Casas, 2010)

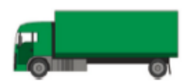
Final simulation calibration parameter values

	Vehicle length (ft)	*Maximum accel. (ft/s^2)*	*Maximum decel. (ft/s^2)*	*FFS mean (ft/s)*	*FFS std. dev. (ft/s)*	*Desired headway mean (sec)*	*Desired headway std. dev. (sec)*	*Intervehicle gap mean (ft)*	*Intervehicle gap std. dev. (ft)*
PC	15	10	15	72.5	3.75	1.5	0.25	10	2.0
ST	30	5	10	67.5	3.75	2.5	0.25	14	2.0
MT	45	4	5	62.5	3.75	3.0	0.25	16	2.5
LT	65	3	3	57.5	3.75	3.5	0.25	20	2.5

Notes: Acceleration of first vehicle in queue (in ft/s^2): 7.0 for passenger car, 5.0 for small truck, 4.0 for medium truck, 3.0 for large truck. FFS = Free Flow Speed.

Yang et al. (2016) analyzed truck acceleration rate and lane length at metered on-ramps. The study was done to analyze the poor acceleration rate of heavy vehicles such as tractor-trailer trucks currently not considered in AASHTO manual. The study used field data to collect truck acceleration rate at two metered on-ramps in the San Francisco Bay Area, California. The truck types classifications used in the study are shown in Table 9.

Table 9 Truck Types (Yang et al., 2016)

Truck type defined in this study	FHWA vehicle classification	Vehicle description	Typical model
Light truck	Class 5	Single unit 2-axle trucks	
Medium truck	Class 6 & 7	Single unit, 3 or more axles trucks	
Heavy truck	Class 8 & 9	Single trailer, 3, 4, 5 axles trucks	

The truck acceleration rates observed by distance from starting point are shown in Table 10.

Table 10 Truck Acceleration Data (Yang et al., 2016)

Truck acceleration performance data.

Truck type	Sample size	Piecewise-constant average acceleration rates (ft/s^2)							0–500 ft. Average acceleration rate (ft/s^2)				
		a_{0-20}	a_{20-50}	a_{50-100}	$a_{100-200}$	$a_{200-300}$	$a_{300-400}$	$a_{400-500}$	Mean	S.D.	15 th %	50 th %	85 th %
Light	44	4.79	4.03	3.57	3.05	2.49	2.59	2.59	2.93	0.85	1.92	2.84	3.77
Medium	114	3.78	3.31	3.17	2.67	2.13	2.17	2.24	2.51	0.68	1.85	2.44	3.23
Heavy	71	2.12	1.97	2.04	1.91	1.91	1.94	1.86	1.93	0.42	1.56	1.96	2.24

Note: S.D. is standard deviation of the mean acceleration rate of each group; 15th % and 85th % represent for the 15th percentile and 85th percentile acceleration rate of each group.

The study concluded that ramp metering has significant impact on trucks compared to passenger cars as a result of trucks' poorer acceleration rates and therefore longer acceleration distances are desired to accelerate to the desired merge speed when trucks are present. The study also noted that the median acceleration rates of light, medium, and heavy trucks at the study metered on-ramps are approximately 2.84 ft/s^2, 2.44 ft/s^2, and 1.96 ft/s^2, respectively.

In the report *Calibration of Microsimulation Models for Multimodal Freight Networks*, Appiah et al (2012) provide VISSIM calibration values for heavy vehicles for Interstate 80 in California (96% cars and 4% Trucks) . Table 11 illustrates the assumed heavy vehicles in the model and the corresponding percentages. It is stated in the report that analytical procedures of the Highway Capacity Manual do not adequately provide guidance for roadway sections with heavy vehicle volumes in excess of 25%, and, therefore, the calibration process using mean absolute percentage error (MAPE) was used to measure the effectiveness of the calibrated values.

Table 11 Truck Traffic Composition (Appiah et al, 2012)

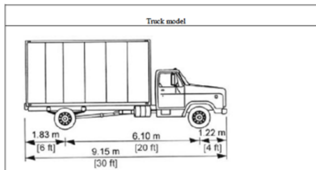
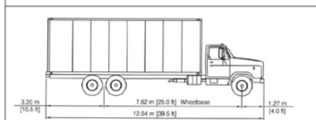
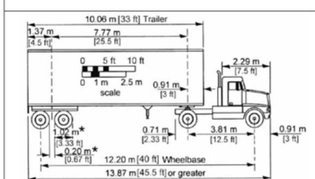
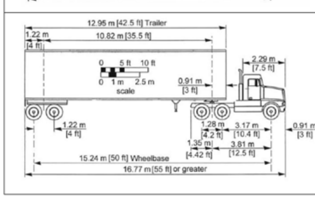
Truck model	Name (Composition)
	2-axle single unit truck (31.3%)
	3-axle single unit truck (36.2%)
	Intermediate semitrailer (WB-40) (27.5%)
	Intermediate semitrailer (WB-50) (5.0%)

Table 12 below shows the calibrated values used by the researchers. It is noted that the lowest value of the MAPE after 100 iterations was 6.5%.

Table 12 Calibrated VISSIM Parameters (Appiah et al, 2012)

Standstill distance (CC0): 1.1 m	
Parameter	Calibrated Value
Standstill distance (CC0)	1.1 m
Headway time (CC1)	0.3 s
"Following" variation (CC2)	2.6 m
Threshold for entering "following" mode (CC3)	-9.0 s
"Following" threshold (CC4)	-0.29 ms$_{-1}$
"Following" threshold (CC5)	0.30 ms$_{-1}$
Speed dependency of oscillation (CC6)	11.95 rad$_{-1}$
Oscillation acceleration (CC7)	0.20 ms$_{-2}$
Standstill acceleration (CC8)	2.78 ms$_{-2}$
Acceleration at 80 km/h (CC9)	1.83 ms$_{-2}$
Waiting time before diffusion	20.5 s
Emergency stop position	4.7 m
Safety distance reduction factor	0.41

Dorado et al. (2014) analyzed the relationship between TSP call distance and traffic congestion on bus route by using varying approach volume to capacity (v/c) ratios and measuring bus delay. Green extension, red truncation, or a combination of both were the TSP strategies tested. Priority was set to be requested on any legs of the intersection and signal timing plans were coordinated by adjusting force-offs.

The conditions set during the analysis included fifteen-minute bus headway, a near side and far side bus stop, and a fixed time, two phase signal with a 70 second cycle time. The researchers used SYNCHRO software to identify the volume to capacity (v/c) ratios (1.1, 0.9, 0.7, and 0.5) for traffic and VISSIM software to perform stimulation and extract results.

Detector call distance of 420ft, 350ft, and 280ft from stop bar were tested during a 12-hour run with 900 seconds warm up with TSP implemented so that it would be activated every time. The study concluded that for far side stop, the percentage of buses that experienced wait time went down from 35% at 280ft to 31% at 420ft and that for near side stop, the 350ft call distance provided the best results. It was, however, also concluded that further call distance had benefits for far side stops only and that the best call distance for near side stops was shown to be a distance related to the green time extension. The study also concluded that the relationship of the congestion in a given intersection and the call distance worked best up to a v/c of approximately 0.9 with the optimal benefits at a v/c of approximately 0.7.

Ngan et al. (2004) determined that TSP had a moderate impact on cross-street performance where the v/c ratio was above 0.8, while this impact was significant for v/c greater than 0.9.

Wolput et al. (2016) developed an optimal cycle length formula that could be applied for under-saturated, near-saturated, and oversaturated isolated intersections. The study compared the new optimal cycle length formula with Webster's formula shown below, which was noted to be suitable for under-saturated conditions only as a result of its asymptotical formulation.

Table 13 Optimal Cycle Length (Wolput et al., 2016)

Webster Formula	$C_{opt} = \frac{\beta_L \cdot L + \beta_1}{\beta_0 - \beta_Y \cdot Y}$
New Optimal Cycle Length Formula	$C_{opt} = \frac{100}{5.146 - 4.625 \cdot Y - 0.1045 \cdot L + 0.09483 \cdot Y \cdot L}$

C_{opt}: Optimal Cycle Length, L: Lost Time, Y: Intersection Flow Ratio

The regression formulas can be applied to minimize vehicle delay (Webster), or minimize delay, queue length, fuel consumption, performance index that combines the operational cost of stops and delay (Akcelik) or user preference critical intersection flow ratio (HCM).

The following variables: intersection flow ratio, flow ratio of the transit phase, transit frequency, distance of the priority detector from the intersection stop bar, and total lost time were used to analyze the impact on optimal green splits and cycle lengths through a sensitivity analysis using CAPACITEL. A regression analysis for the optimal cycle length was then undertaken followed by a validation in VISSIM.

The study concluded that the new optimal cycle formula was most beneficial for intersections with higher flow ratios and intersections with multiple phases. It also concluded that for TSP strategies such as green extension or phase rotation with green extension, the TSP implementation did not affect the cycle length optimization. It was also concluded that neither the frequency of buses nor the presence of conflicting lines have any impact on optimal signal settings for the considered range between 0 and 60 transit vehicles per hour and detector distances below 35 seconds of free flow travel time from the stop bar. Intersection flow ratio, lost time, and their correlation were concluded to be the relevant parameters in the regression analysis. It was noted that the new formula showed an average reduction of delay per person of 4 seconds for two phases, 18.8 seconds for three phases and 31.2 seconds for four phases.

The study also notes that near side transit stops were not included in the analysis and that in order for the formula to be valid, the amount of total travel time from detector to stop bar, should be below 30 seconds of free flow travel time from the stop bar.

Buck, et al (2016) provides a strategy for calibrating VISSIM in order to reproduce realistic control delay values. It uses video measurements were taken at four signalized intersections in

Germany to validate results. Three measures that are relevant for realistic behavior at intersections were identified as the time to pass intersection, the average headway, and the arrival distribution of the vehicles. The study concluded that the calibration of time to pass intersection had only a minor effect on total delay. The effect of the average headway on total delay was much greater. As the default arrival time distribution in the simulation differed substantially from the arrival time distribution observed in reality, adjustment of the arrival time distribution had the greatest influence on delay. The study also notes that for VISSIM, using the Wiedemann 99 model, parameter values in the range from 2.0 m to 2.5 m for CC0 and in the range from 1.3 s to 1.4 s for CC1 achieved good results for the average headway at the signalized intersections used in this study.

Based on the findings of the studies reviewed and summarized in this section, it is noted that only green extension has previously been proven beneficial for oversaturated conditions, while in near-saturated conditions, green extension, phase insertion, phase insertion with green extension and phase rotation with green extension have all been proven beneficial. It is also concluded that effectiveness of green extension TSPs have proven to be more successful for far side bus stops compared to near side bus stops. With regards to cycle length, it is concluded that longer cycle lengths result in lower impacts of the TSP strategies on cross street traffic and that higher green time to cycle length ratio result in lower impact of the TSP strategies on cross street traffic. Other studies have also stated the impact of various parameters such as bus frequency that will be considered in this study. Based on the findings of the HCM, truck acceleration rates are significantly different from the default VISSIM values, and, therefore this study will consider the HCM truck acceleration parameters.

3. Research Methodology

A brief summary of the research methodology is shown in the flow chart below. As shown, the study includes two conditions tested in VISSIM software at an isolated intersection during near-saturated and over-saturated traffic conditions. Each of these conditions were tested using two TSP strategies, namely Queue Jump Lanes with Advanced Transit Signal (Phase Insertion strategy) (QJL-TS) and Green Extension (GE), which were compared to a based scenario including no TSP strategy. Other variables tested in each scenario includes bus headways of 5, 10, and 15 minutes as well as truck composition consisting of 5%, 10%, 15%, and 20% heavy trucks.

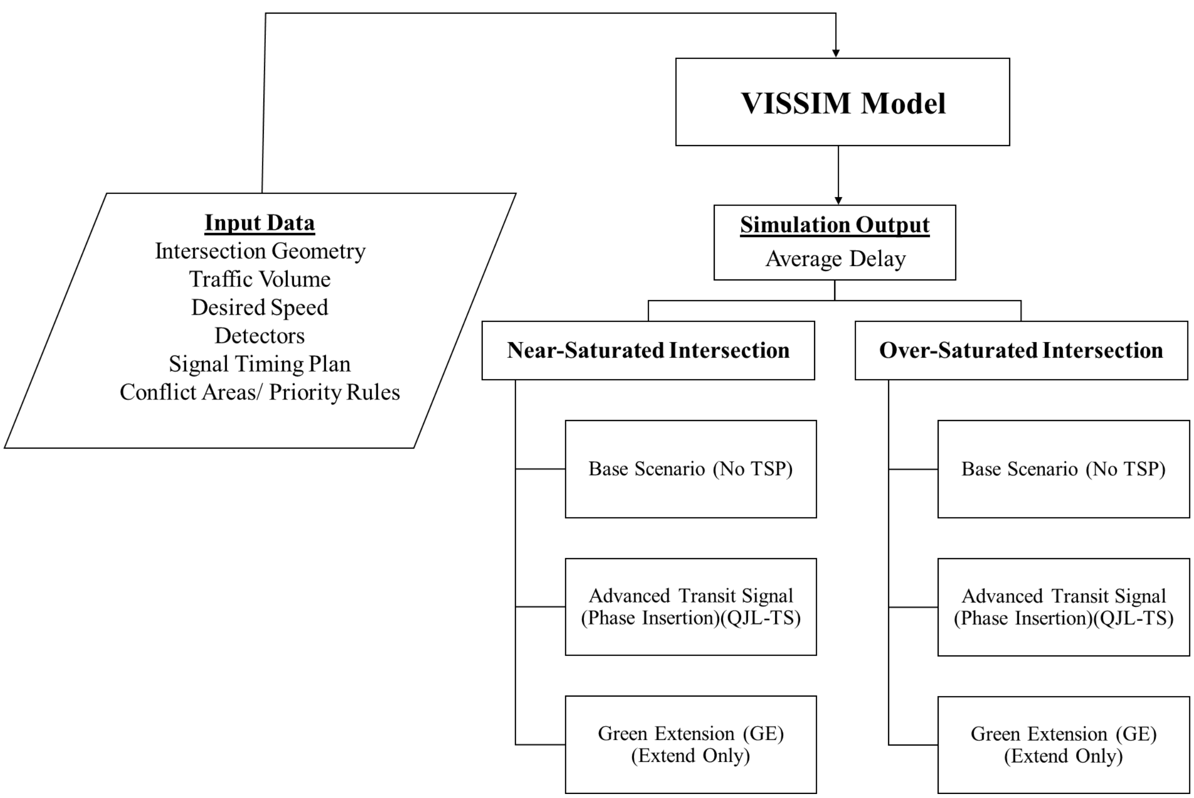


Figure 3 Research Framework

3.1 Traffic Simulation and Optimization Models

Micro-simulation modelling allows the modeler to simulate a road network and study the impacts of various scenarios including any improvements made to the network. PTV-VISSIM (Verkehr In Städten - SIMulationsmodell ("Traffic in cities - simulation model")) software is a widely used multimodal microsimulation software developed by PTV Planung Transport Verkehr AG in Germany. PTV-VISSIM (VISSIM) 9 was chosen for this study for its strong transit modelling capabilities and its flexible TSP modules (Hao, 2013).

Synchro is a deterministic software which use formulas, such as the Highway Capacity Manual (HCM) methodologies, for capacity analysis. Synchro was developed by Trafficware and is widely used for applications such as signal timing optimizations by various municipalities in Canada, such as the City of Toronto (City of Toronto, 2019).

VISSIM is a stochastic software that simulates the coded transportation network, measuring the performance of individual vehicles as they move through the system, while synchro is a deterministic software which provides specific solutions given specific inputs like geometry and volume. This study, therefore, uses Synchro software to obtain optimized signal timing plans for an isolated intersection, while using the VISSIM software to code truck behavior, such as acceleration rate, and obtain delay results for each of cars, trucks (HGV), and buses.

3.1.1 Model Geometric Parameters

Network coding includes the building of road network and the placement of signal heads and other objects in the model. This section summarizes the network coding in VISSIM for this study.

The road network consisted of the coding the intersection which was set up to represent a typical major arterial intersection in the Greater Toronto Area (GTA) area with three lanes in each direction including right and left turn lanes for the major E-W movement and the minor N-S movement (Figure 4).

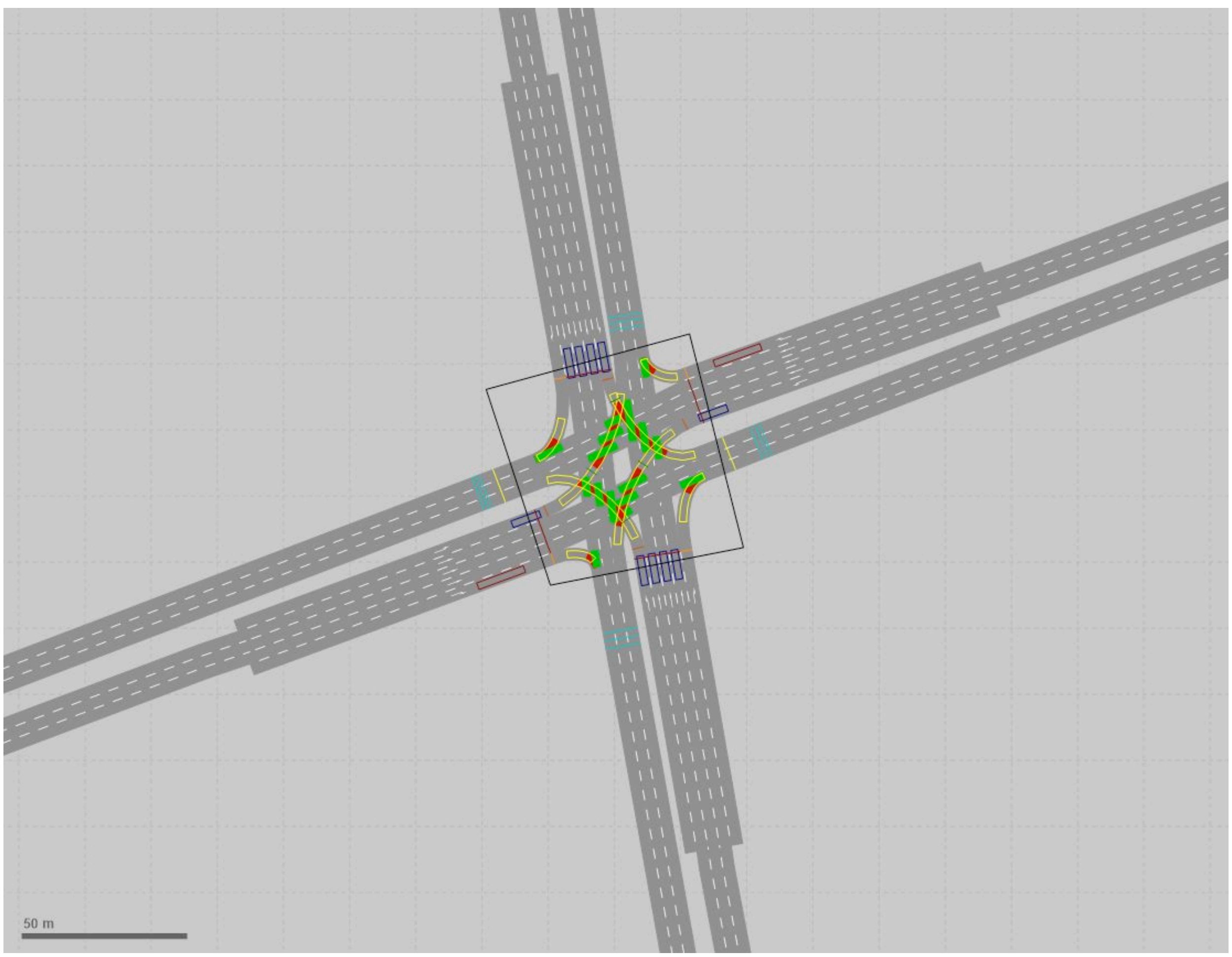


Figure 4 Intersection Layout in VISSIM

The signal heads and their respective timings, which use the RBC NEMA phasing, were imported from Synchro software, discussed further in section 3.3. As the isolated intersection was coded with a semi-actuated signal plan, detectors were also placed on the minor road and the on the left turn lanes for the major road. Conflict areas are regions where overlapping links and connectors exist, conflict areas were coded for each of the right and through and left and through movements (shown as green and red areas in Figure 4). Priority rules, normally used for conflicting traffic flows which are not controlled by signals, were modelled at the intersection to keep the intersection clear of conflicting traffic. Reduced speed areas, 20 km/h for right turn and 25 km/h for left turn, were also coded for each of the right and left turn movements. Further, the intersection was coded to include pavement markings, desired speed decisions, vehicle inputs, static routing decisions, and transit stops.

3.1.2 Model Input Parameters and Model Calibration

The VISSIM analysis included a total of 5400 simulation seconds (including 1800 seconds warm up) and each scenario was tested for ten runs with different random number seeds. Heavy trucks characteristics, such as acceleration rates, were modified in VISSIM to match FHWA Class 9 truck types with a typical weight-to-power ratio of 110 Ib/hp as stated in HCM 2016. FHWA Class 9 trucks were chosen based on their size and available acceleration rate data as they are typically larger than buses and more likely to affect transit operation and right of way. Bus acceleration rate was also modified to 3.3 ft/s^2 (1.01 m/s^2) as per HCM guidelines.

The intersection volumes, shown in Figure 5 and Figure 6, were set in Synchro software to obtain an optimized signal timing plan for a semi-actuated intersection with 120 second of cycle length for near-saturated and over-saturated conditions. It was assumed that the peak movements for the simulation are eastbound and northbound, however, as EB-WB road is a major road, the westbound movement was also assumed to have similar traffic volume.

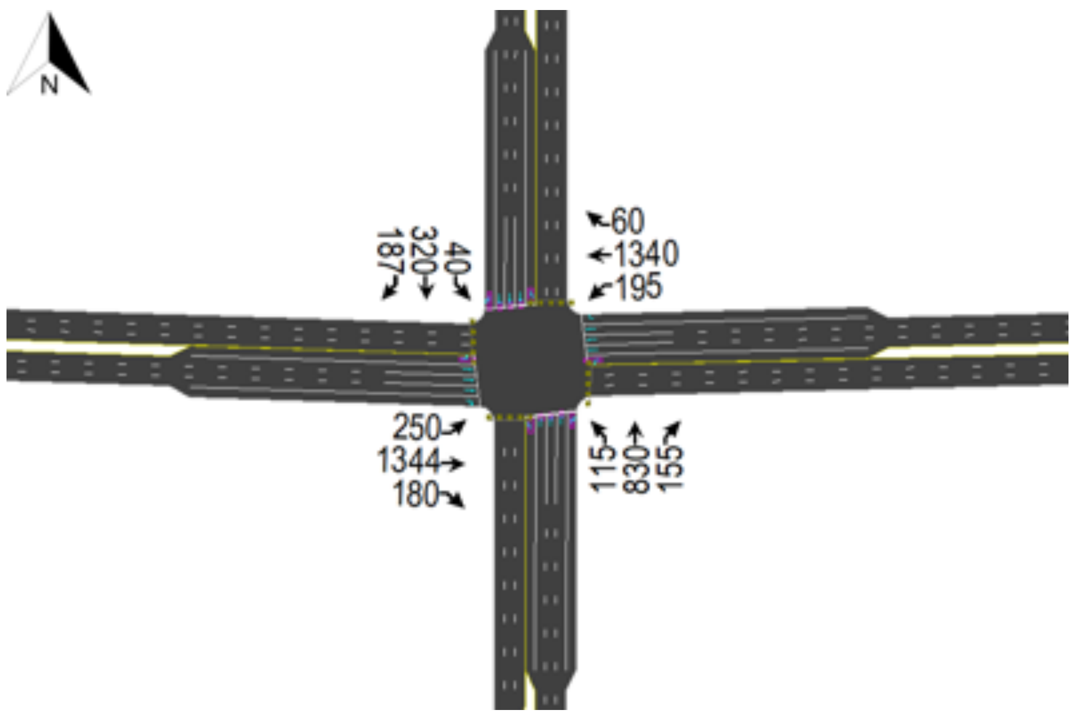


Figure 5 Traffic Volume - Near-Saturated Conditions

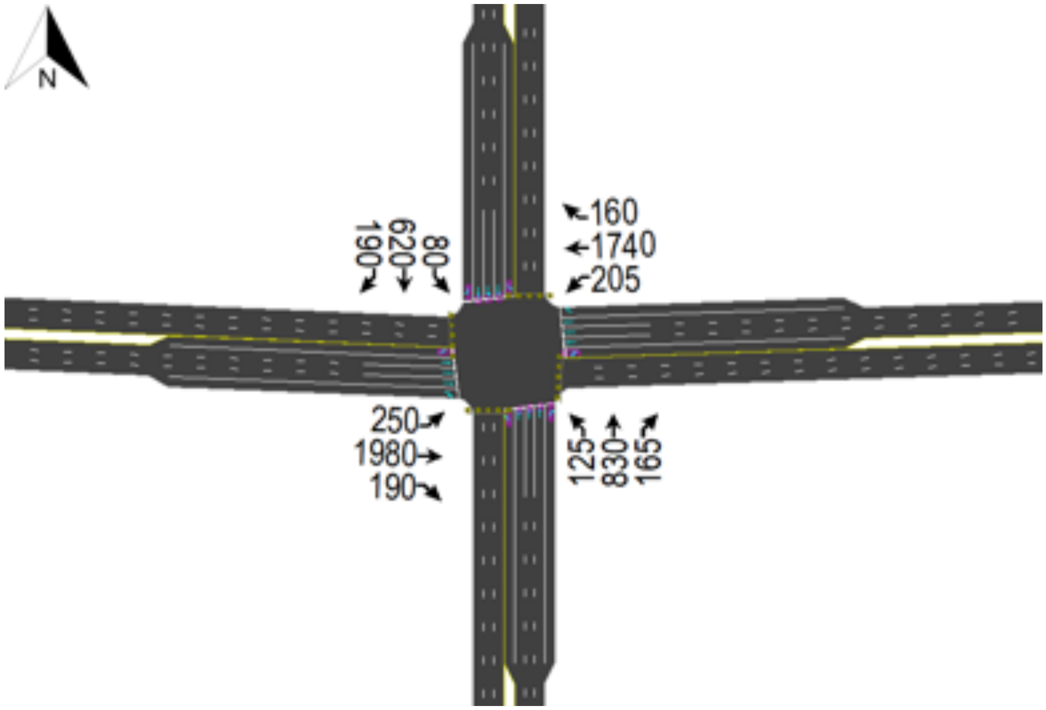


Figure 6 Traffic Volume - Over-Saturated Conditions

The signal timing plans for each of the scenarios (near-saturated and over-saturated) is shown in Figure 7 and Figure 8 below.

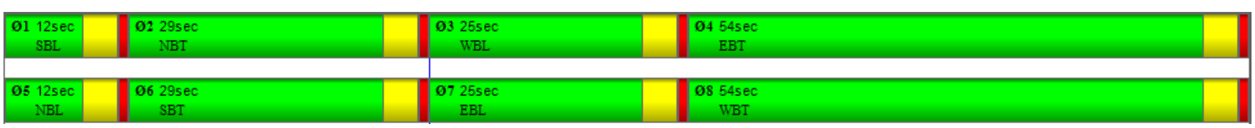


Figure 7 Signal Timing Plans - Near-Saturated Conditions

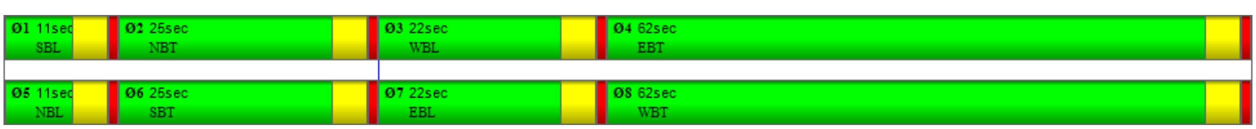


Figure 8 Signal Timing Plans - Over-Saturated Conditions

The arterial speed was set at 60 km/h and cross-street volume/ capacity ratio was kept constant at 0.85 and truck percentage for the cross street were also kept constant at 2%. VISSIM's default value of 20 seconds (normal distribution with standard deviation of 2) was used for bus dwell times. The length of the turn lanes were determined using the 95th percentile queue output in Synchro to ensure that queues would not hinder transit from using the near side bus stops.

In order to ensure that the model is running properly, the model was calibrated for each scenario using the GEH statistic. The GEH Statistic is a formula (shown below) used in traffic engineering and traffic modelling to compare two sets of traffic volumes. A GEH of five and under is considered a good fit and is acceptable by most agencies in Canada.

$$GEH = \sqrt{\frac{2(m-c)^2}{m+c}}$$

Notes:
m = output traffic volume from the simulation model (vph)
c = input traffic volume (vph)

3.2 Preliminary Analysis

A preliminary analysis was undertaken to compare the following TSP strategies: queue jump lane combined with advanced transit signal (Phase Insertion), green extension (GE) (Early/Extend), Green extension (Extend Only), and a combination of both advanced transit signal and green extension. The preliminary analysis was undertaken for the near saturated (v/c =0.85) conditions with a bus headway of 15 minutes and truck percentage of 5% on the main road.

Based on the findings of the preliminary analysis and the studies reviewed and summarized in the Literature Review section of this report, it was concluded that queue jump lane combined with advanced transit signal and green extension (Extend Only) have the lowest impact on side street traffic. It was also concluded that green extension (Early/Extend) has the highest benefit for bus performance (27% decrease in vehicle delay for near side bus stop and 19% decrease in vehicle delay for far side bus stop), followed by green extension (Extend Only) and queue jump lane combined with advanced transit signal, with queue jump lane combined with advanced transit signal showing least benefit and green extension (Extend Only) having little benefit in scenarios including a far side bus stop.

It was, therefore, concluded that the study should further analyze the impact of truck percentages comparing only two TSP strategies, namely queue jump lane combined with advanced transit signal (Phase Insertion) (QJL-TS) and green extension (GE) (Extend Only).

3.3 Alternative Scenarios

As part of the study, a total of one hundred and forty-seven (147) scenarios, consisting of 48 for near saturated near side bus stop, 36 for over saturated far side, 36 for over saturated near side bus stop, 27 for over saturated far side bus stop, were tested using a combination of the variables described in Table 14 and the previously mentioned QJL-TS and GE TSPs:

Table 14 Alternative Scenario Variables

Variable Description	Variable Values
Intersection v/c	Near saturated (v/c =0.85), over saturated (v/c =1.00)
Bus Headway	5, 10, 15 minutes (hourly bus volume of 12, 6, 4 respectively)
Truck Percentage	5%, 10%, 15%, 20%*

*Intersection volumes kept constant

The QJL-TS scenario included a ten (10) second advanced green time upon the detection of a bus using a presence detector. For the QJL-TS Scenario, a signal phase, named "Bus" was added. The 10-second advanced phase would be activated every time transit reaches the signal using a presence detector.

The GE scenario was tested using a ten (10), twenty (20), and thirty (30) second extension upon the detection of bus using check-in/ check-out detectors placed at a distance to Stop Bar using the following equation: Approaching Speed × (Max Green Extension - Dwell Time) while the check-out detector was placed at the center of the intersection (Hao, 2013). For the GE Scenario, the Transit Priority option was activated using check in/ check out detectors and an extension of 30 seconds upon the detection of transit.

As the study focused on the vehicle delay experienced by transit at the intersection, the performance measure used in this study is average vehicle delay (in seconds) experienced by cars, trucks, and transit at the intersection. Vehicle delay is defined in VISSIM as the average delay of all vehicles, or in other words, the delay obtained by subtracting the theoretical (ideal) travel time from the actual travel time. The theoretical travel time is the travel time which could be achieved if there were no other vehicles and/or no signal controls or other reasons for stops. Deceleration in reduced speed areas is not accounted for in the delay time. It should be noted that the actual travel time does not include any passenger service times of public transit vehicles at stops and no parking time in real parking lots. The delay due to braking before a public transit stop and/or the subsequent acceleration after a public transit stop are, however, part of the delay. (PTV-VISSIM, 2019)

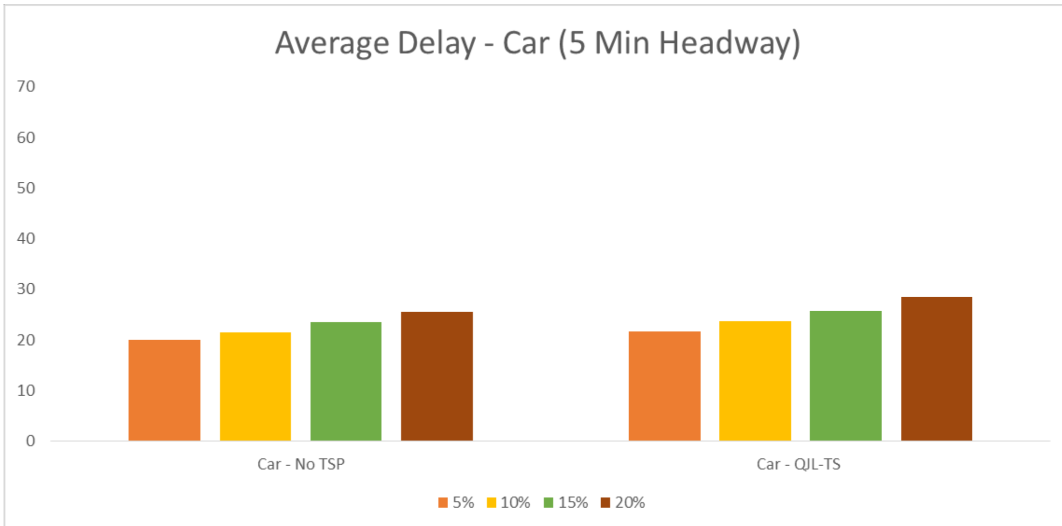
4. Results

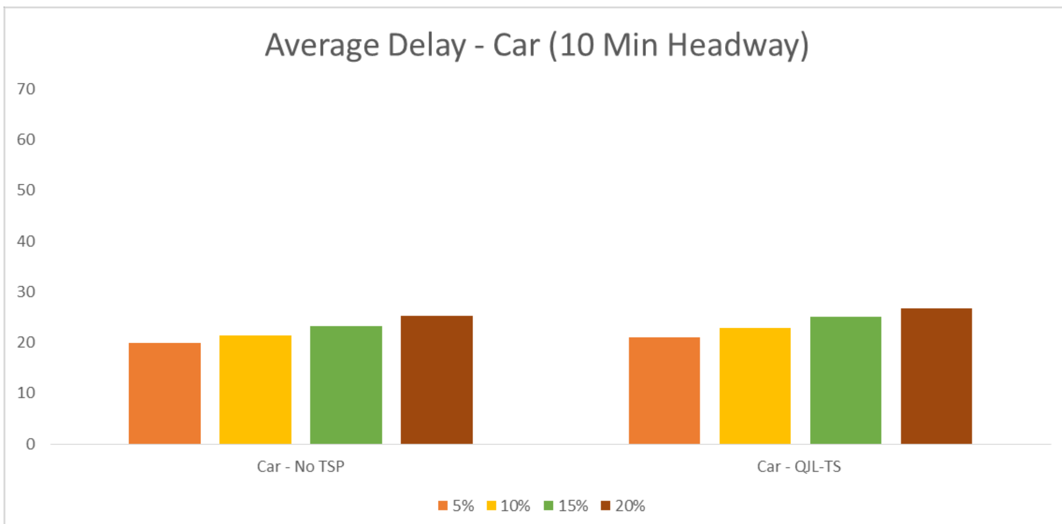
The results of the analysis were divided into two sections for near saturated (v/c =0.85) and over saturated (v/c =1.00) traffic conditions. Each section includes the results for twenty seven (27) scenarios consisting of a combination of bus headways and truck percentages. Each of the near saturated and over saturated traffic condition scenarios are also further divided by the location of bus stops, namely, near-side and far-side bus locations.

4.1 Near-Saturated Intersection

4.1.1 Near-Side Bus Location

The average vehicle delay comparison for the QJL-TS scenario for each of the vehicle classes (cars, trucks, and buses) are shown in Figure 9, Figure 10 and Figure 11, respectively.





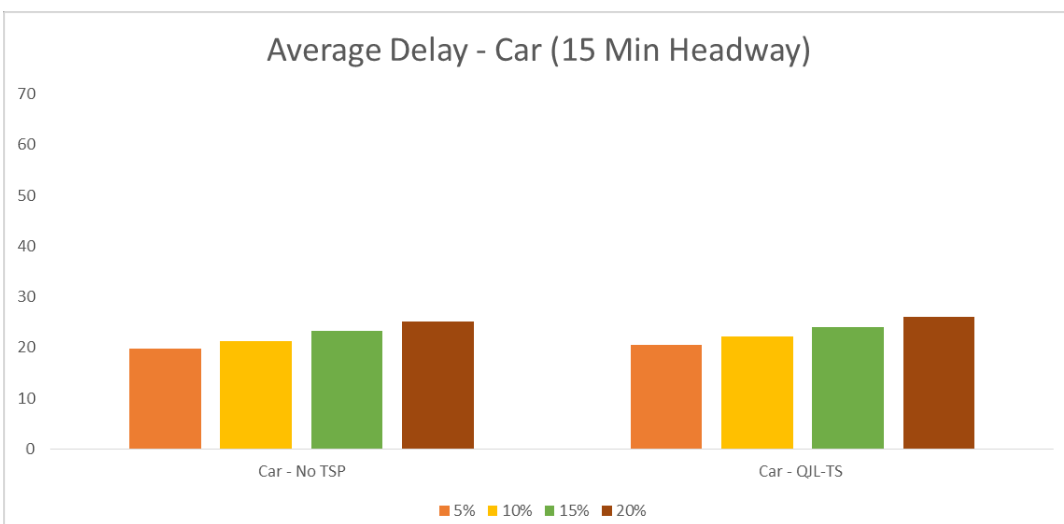


Figure 9 Average Vehicle (Car) Delay vs Truck Percentage – NS – QJL-TS

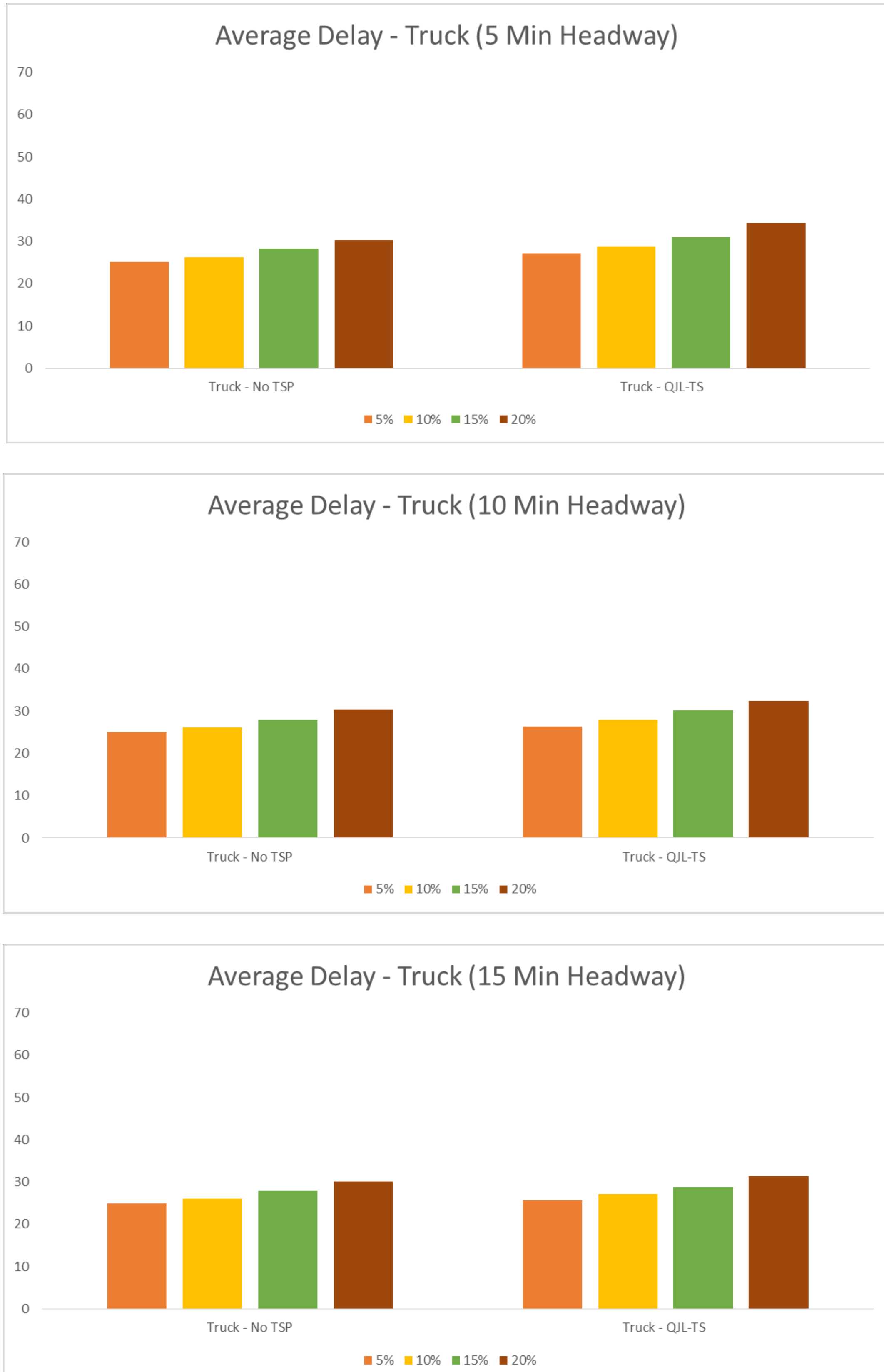


Figure 10 Average Vehicle (Truck) Delay vs Truck Percentage – NS - QJL-TS

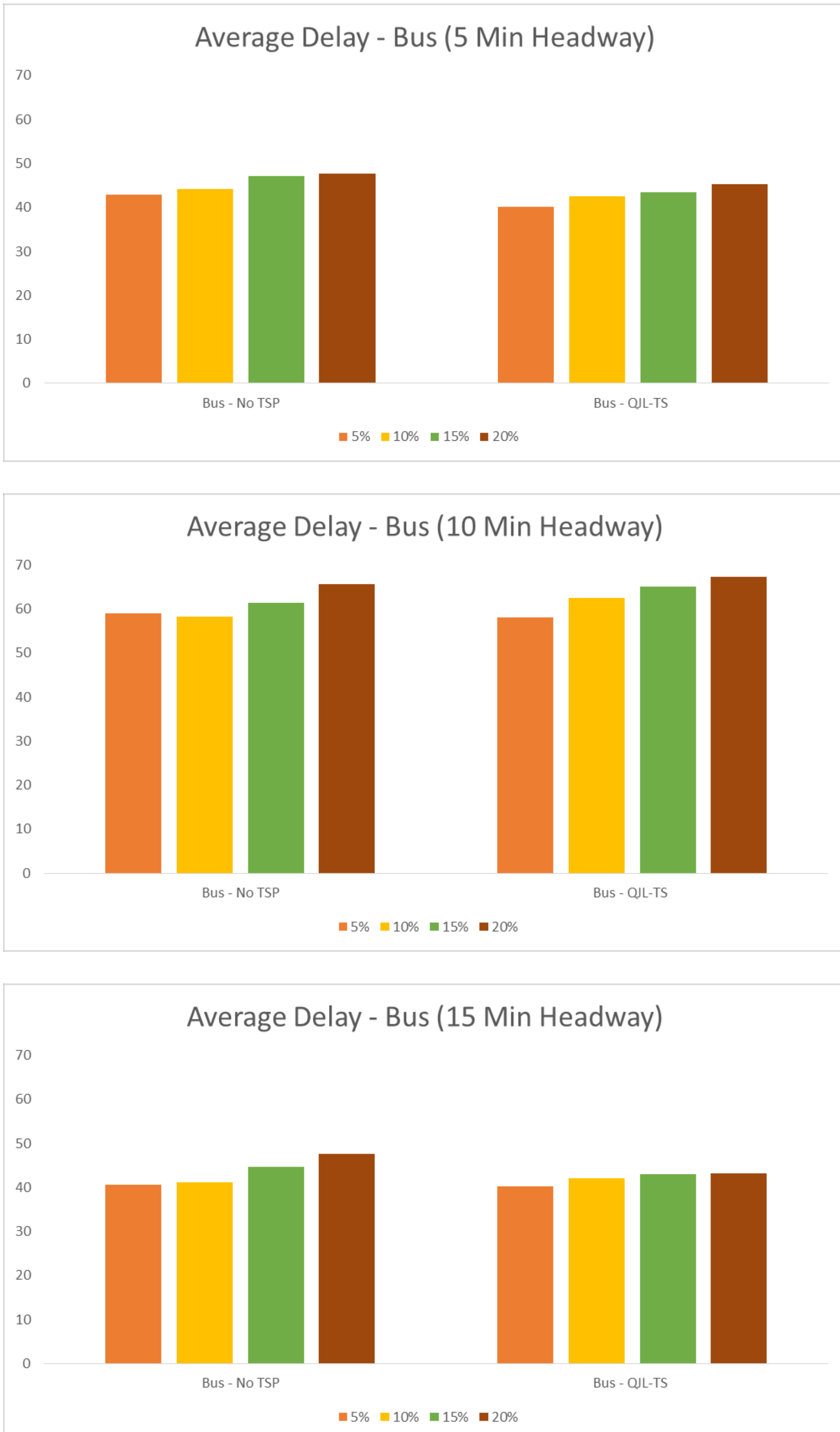


Figure 11 Average Vehicle (Bus) Delay vs Truck Percentage – NS - QJL-TS

The delay values obtained through the microsimulation analysis is shown in Table 15 below:

Table 15 Vehicle Average Delay – NS - QJL-TS - Summary

5-Minute Bus Headway				
Scenario	Truck Percentage			
	5%	10%	15%	20%
Car - No TSP	20.02	21.52	23.46	25.48
Car - QJL-TS	21.69	23.63	25.71	28.45
Truck - No TSP	25.20	26.26	28.23	30.34
Truck - QJL-TS	27.07	28.74	31.09	34.39
Bus - No TSP	42.94	44.22	47.07	47.77
Bus - QJL-TS	40.16	42.56	43.36	45.38

10-Minute Bus Headway				
Scenario	Truck Percentage			
	5%	10%	15%	20%
Car - No TSP	19.90	21.38	23.31	25.32
Car - QJL-TS	20.95	22.83	25.07	26.82
Truck - No TSP	25.14	26.13	28.08	30.47
Truck - QJL-TS	26.37	28.02	30.19	32.44
Bus - No TSP	59.09	58.20	61.39	65.69
Bus - QJL-TS	58.03	62.45	65.05	67.25

15-Minute Bus Headway				
Scenario	Truck Percentage			
	5%	10%	15%	20%
Car - No TSP	19.77	21.29	23.31	25.16
Car - QJL-TS	20.48	22.27	24.01	26.08
Truck - No TSP	24.89	25.99	27.86	30.14
Truck - QJL-TS	25.75	27.23	28.79	31.41
Bus - No TSP	40.66	41.21	44.58	47.54
Bus - QJL-TS	40.21	42.16	43.07	43.27

As shown in the figures and the tables, the higher the truck percentages, the higher the impact on all vehicles, with buses experiencing the highest delay.

Compared to the base scenario (No TSP), the QJL-TS scenario will decrease bus delay by approximately 2% with the highest benefit observed for the 20% truck percentage volume. It should be noted, however, that the TSP for this scenario was coded with the purpose of keeping the cycle length constant without decreasing green time for the side street and, therefore, in some scenario a slight increase of delay can be observed due to buses being unable to activate the presence detector as they are stuck behind a vehicle turning right.

The average vehicle delay (GE scenario – 10 seconds) for each of the vehicle classes (cars, trucks, and buses) are shown in Figure 12, Figure 13 and Figure 14 respectively.

Figure 12 Average Vehicle (Car) Delay vs Truck Percentage - NS – GE10

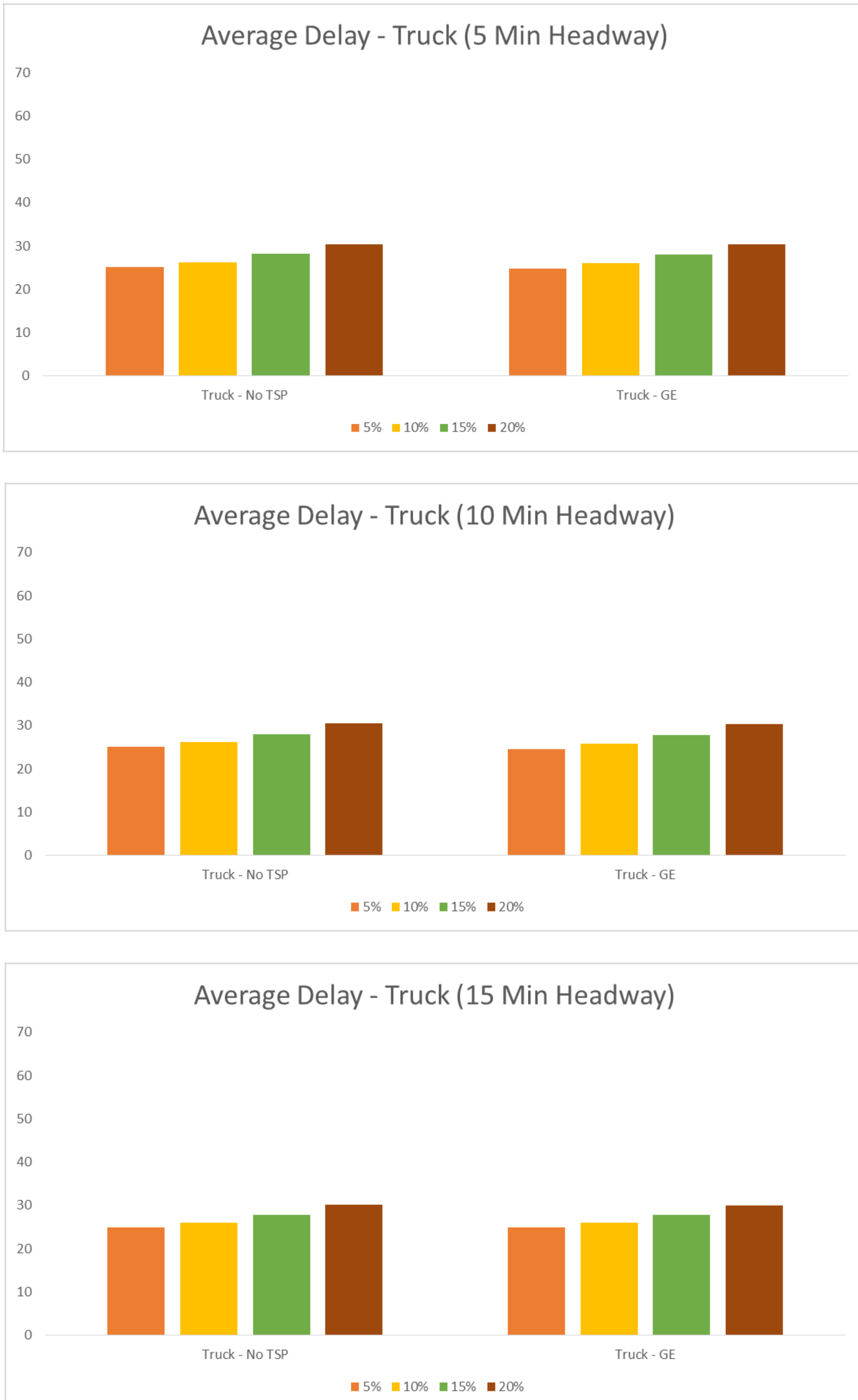
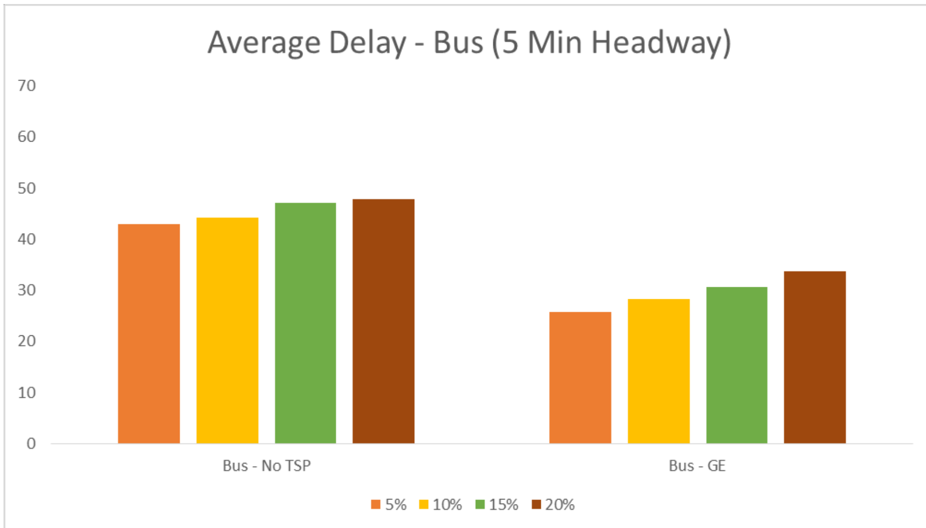
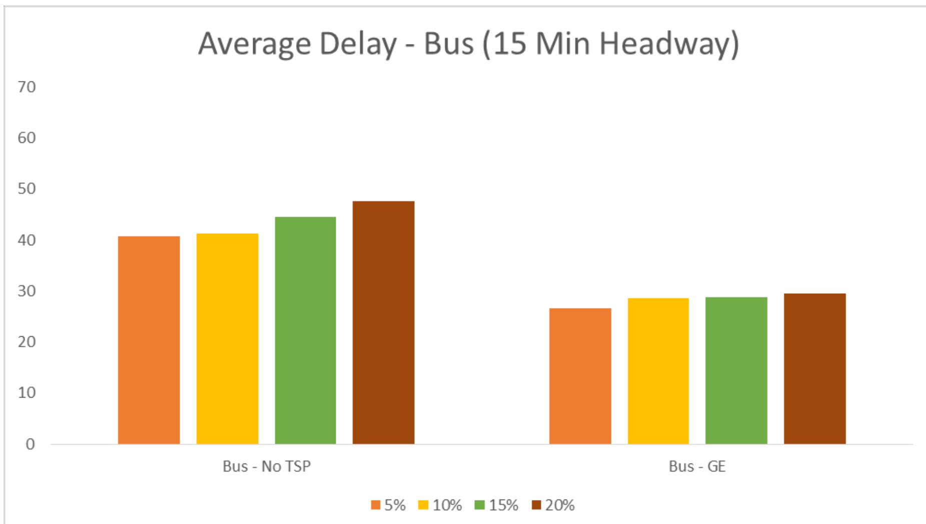


Figure 13Average Vehicle (Truck) Delay vs Truck Percentage - NS – GE10





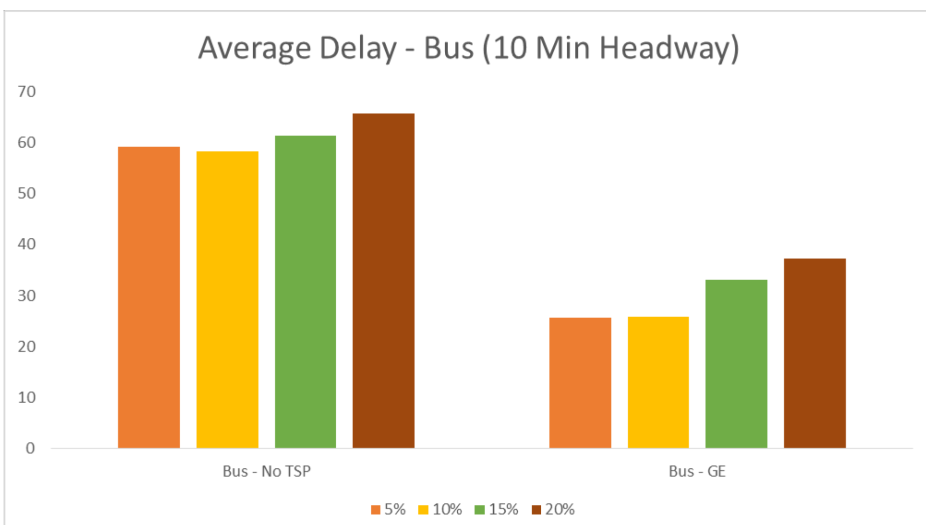


Figure 14 Average Vehicle (Bus) Delay vs Truck Percentage - NS – GE10

The delay values obtained through the microsimulation analysis for the GE scenario – 10 seconds is shown in Table 16 below:

Table 16 Vehicle Average Delay – NS – GE10 - Summary

5-Minute Bus Headway				
Scenario	**Truck Percentage**			
	5%	**10%**	**15%**	**20%**
Car - No TSP	20.02	21.52	23.46	25.48
Car - GE	19.81	21.42	23.16	25.16
Truck - No TSP	25.20	26.26	28.23	30.34
Truck - GE	24.79	26.12	28.02	30.38
Bus - No TSP	42.94	44.22	47.07	47.77
Bus - GE	25.82	28.29	30.71	33.77

10-Minute Bus Headway				
Scenario	**Truck Percentage**			
	5%	**10%**	**15%**	**20%**
Car - No TSP	19.90	21.38	23.31	25.32
Car - GE	19.63	21.25	23.11	25.26
Truck - No TSP	25.14	26.13	28.08	30.47
Truck - GE	24.51	25.74	27.77	30.34
Bus - No TSP	59.09	58.20	61.39	65.69
Bus - GE	25.60	25.86	33.13	37.17

15-Minute Bus Headway				
Scenario	**Truck Percentage**			
	5%	**10%**	**15%**	**20%**
Car - No TSP	19.77	21.29	23.31	25.16
Car - GE	19.75	21.32	23.34	25.07
Truck - No TSP	24.89	25.99	27.86	30.14
Truck - GE	24.97	25.95	27.87	30.05
Bus - No TSP	40.66	41.21	44.58	47.54
Bus - GE	26.70	28.67	28.74	29.48

The results show an average of 40% decrease in delay for buses for the of truck percentages (5%, 10%, 15%, 20%) tested. The results also indicate that other modes will either benefits or not be impacted by the 10 second extension of green upon the detection of buses. The highest benefit was observed for the 5% truck percentage scenario and the 15 minute bus headway.

The average vehicle delay (GE scenario – 20 seconds) for each of the vehicle classes (cars, trucks, and buses) are shown in Figure 15, Figure 16 and Figure 17, respectively.

Figure 15 Average Vehicle (Car) Delay vs Truck Percentage – NS – GE20

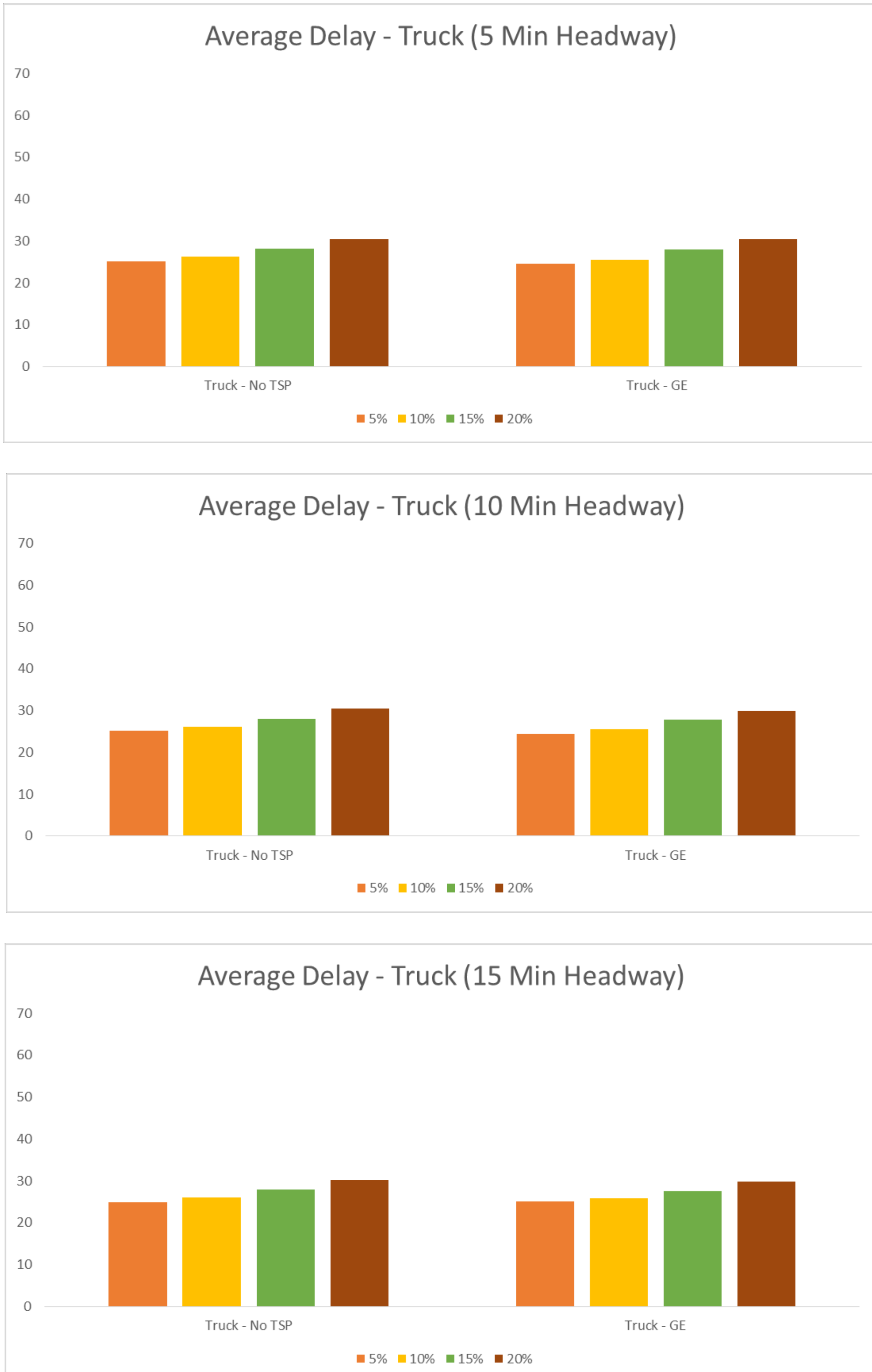
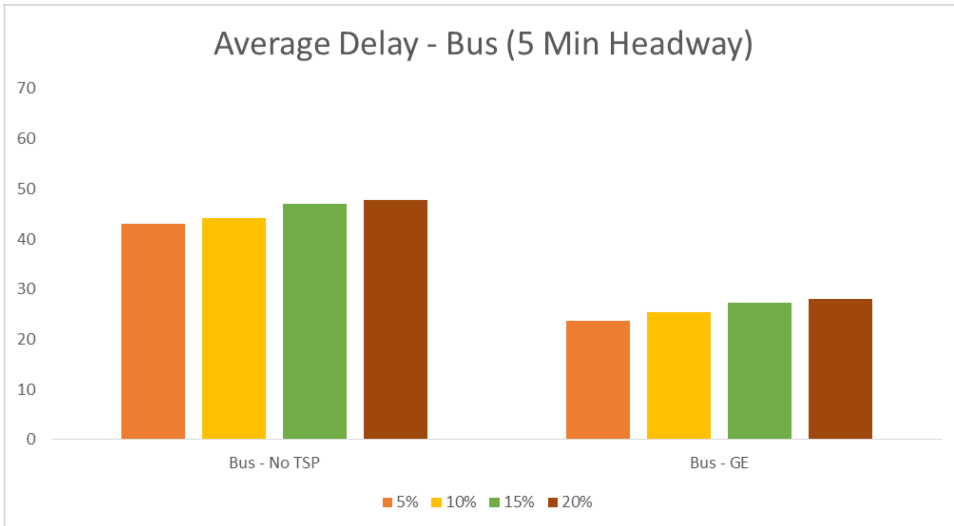
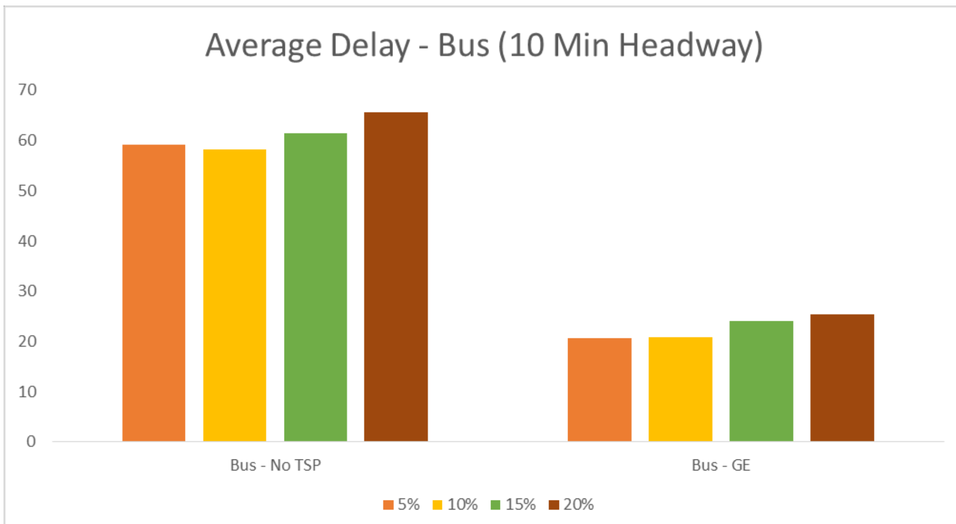


Figure 16 Average Vehicle (Truck) Delay vs Truck Percentage – NS – GE20





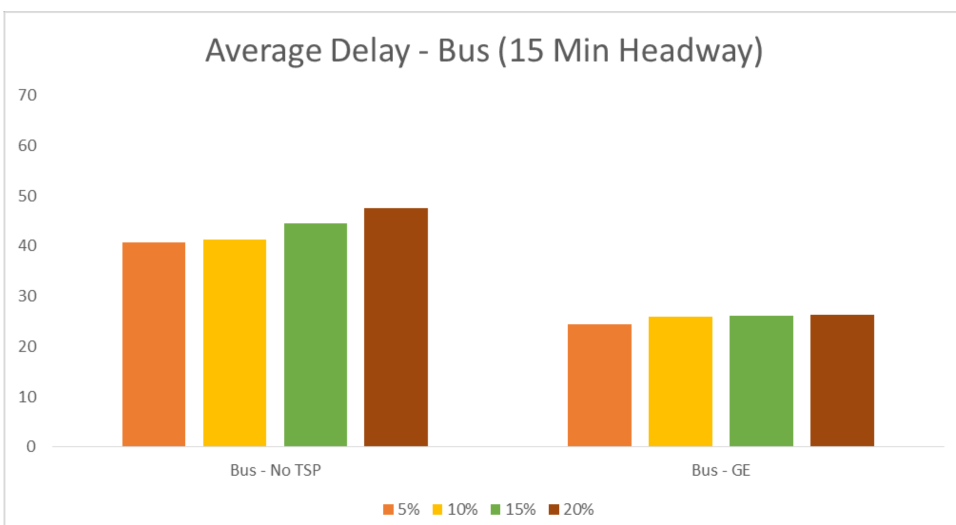


Figure 17Average Vehicle (Bus) Delay vs Truck Percentage – NS – GE20

The delay values obtained through the microsimulation analysis for the GE scenario – 20 seconds is shown in Table 17 below:

Table 17 Vehicle Average Delay – NS – GE20 - Summary

5-Minute Bus Headway				
Scenario	Truck Percentage			
	5%	10%	15%	20%
Car - No TSP	20.02	21.52	23.46	25.48
Car - GE	19.55	21.07	22.89	24.88
Truck - No TSP	25.20	26.26	28.23	30.34
Truck - GE	24.52	25.52	27.90	30.34
Bus - No TSP	42.94	44.22	47.07	47.77
Bus - GE	23.65	25.37	27.26	28.05

10-Minute Bus Headway				
Scenario	Truck Percentage			
	5%	10%	15%	20%
Car - No TSP	19.90	21.38	23.31	25.32
Car - GE	19.40	20.99	22.92	24.76
Truck - No TSP	25.14	26.13	28.08	30.47
Truck - GE	24.39	25.52	27.89	29.87
Bus - No TSP	59.09	58.20	61.39	65.69
Bus - GE	20.60	20.88	24.01	25.45

15-Minute Bus Headway				
Scenario	Truck Percentage			
	5%	10%	15%	20%
Car - No TSP	19.77	21.29	23.31	25.16
Car - GE	19.69	21.17	23.08	24.95
Truck - No TSP	24.89	25.99	27.86	30.14
Truck - GE	24.99	25.89	27.47	29.86
Bus - No TSP	40.66	41.21	44.58	47.54
Bus - GE	24.34	26.01	26.14	26.37

Based on the results shown in Table 15-17 and Figure 15-17, the addition of 20 seconds of green extension upon detection of buses will decrease bus delay by an average of 49% for all the truck percentages tested. The highest benefit was also observed for the 5% truck percentage scenario and the 15 minute bus headway.

The average vehicle delay (GE scenario – 30 seconds) for each of the vehicle classes (cars, trucks, and buses) are shown in Figure 17, Figure 18 and Figure 19, respectively.

Figure 17 Average Vehicle (Car) Delay vs Truck Percentage – NS – GE30

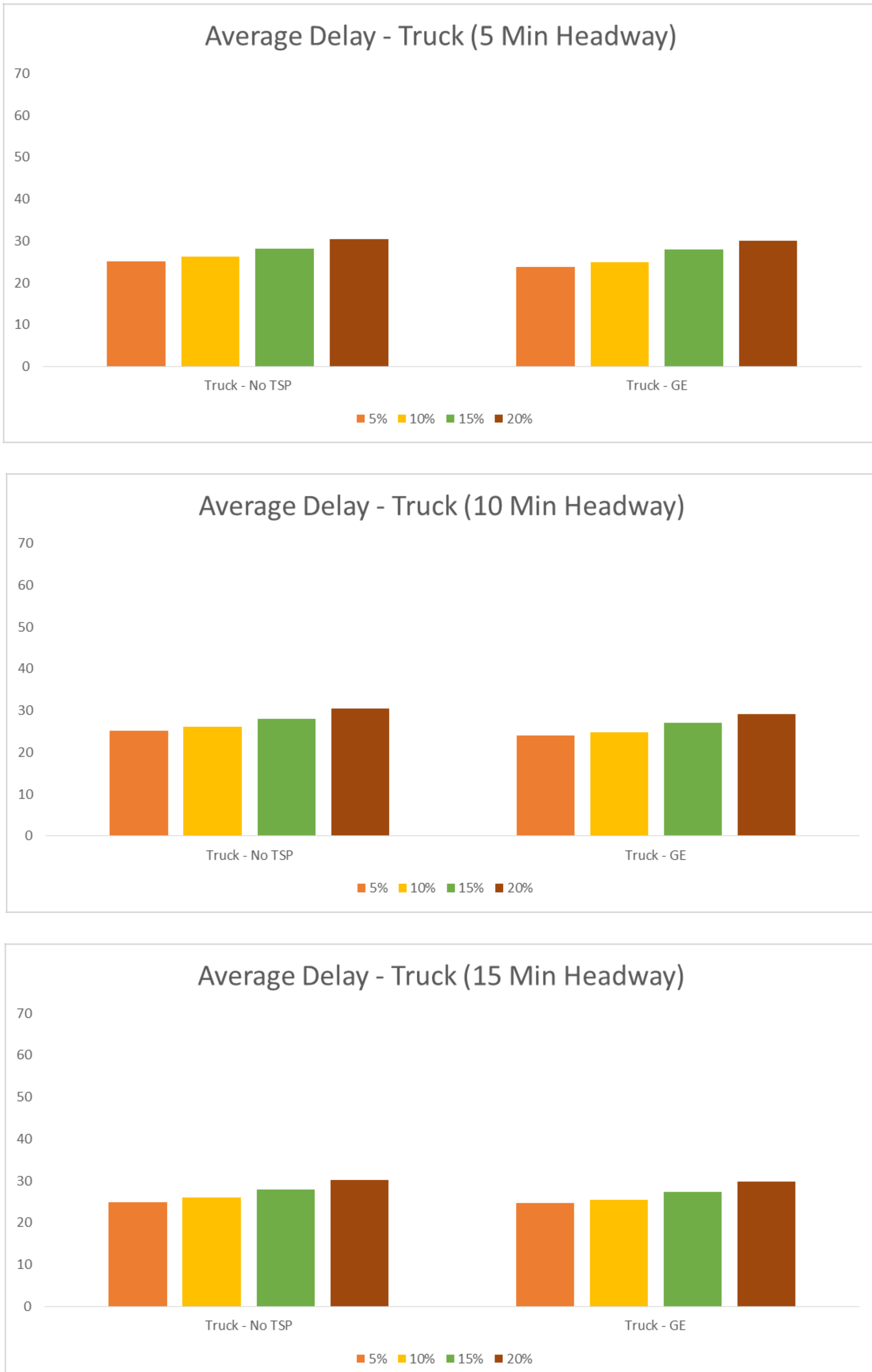


Figure 18 Average Vehicle (Truck) Delay vs Truck Percentage – NS – GE30

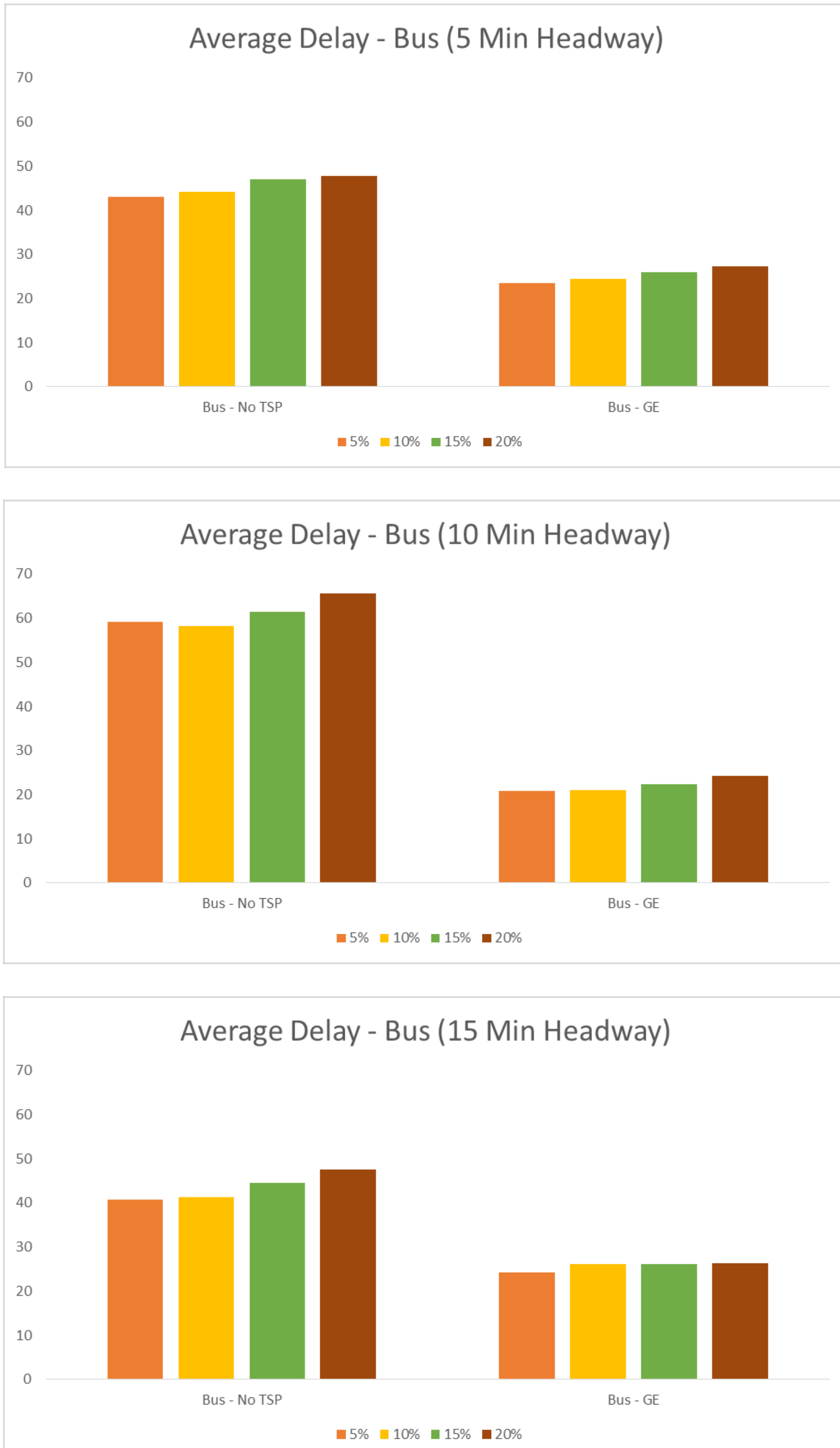


Figure 19 Average Vehicle (Bus) Delay vs Truck Percentage – NS – GE30

The delay values obtained through the microsimulation analysis for the GE scenario – 30 seconds is shown in Table 18 below:

Table 18 Vehicle Average Delay – NS – GE30 - Summary

5-Minute Bus Headway				
Scenario	Truck Percentage			
	5%	10%	15%	20%
Car - No TSP	20.02	21.52	23.46	25.48
Car - GE	19.21	20.68	22.90	24.73
Truck - No TSP	25.20	26.26	28.23	30.34
Truck - GE	23.87	24.85	27.87	29.98
Bus - No TSP	42.94	44.22	47.07	47.77
Bus - GE	23.58	24.53	25.94	27.28

10-Minute Bus Headway				
Scenario	Truck Percentage			
	5%	10%	15%	20%
Car - No TSP	19.90	21.38	23.31	25.32
Car - GE	19.17	20.56	22.47	24.35
Truck - No TSP	25.14	26.13	28.08	30.47
Truck - GE	23.95	24.74	27.15	29.20
Bus - No TSP	59.09	58.20	61.39	65.69
Bus - GE	20.87	20.96	22.43	24.29

15-Minute Bus Headway				
Scenario	Truck Percentage			
	5%	10%	15%	20%
Car - No TSP	19.77	21.29	23.31	25.16
Car - GE	19.48	20.92	22.96	24.90
Truck - No TSP	24.89	25.99	27.86	30.14
Truck - GE	24.77	25.52	27.37	29.79
Bus - No TSP	40.66	41.21	44.58	47.54
Bus - GE	24.27	26.20	26.20	26.35

Based on the results shown above, the addition of 30 seconds of green extension will decrease bus delay by approximately 50% for all the truck percentages with the highest decrease in delay observed during the 5% truck percentage and 15 minute headway.

4.1.2 Far-Side Bus Location

With the far-side bus locations, the near-saturated intersection observed little benefit from the addition of Green Extension TSP. As shown in the tables below (Table 19, Table 20, Table 21), the delay did not decrease for the 5% truck percentage scenario, while the highest benefit was observed during the 20% truck volume analysis with a decrease of 7% (10 second extension – 15 minute headway), 13% (20 second extension – 15 minute headway), and 13% (30 second extension – 15 minute headway).

Table 19 Vehicle Average Delay – NS – GE10 - Summary

5-Minute Bus Headway				
Scenario	**Truck Percentage**			
	5%	**10%**	**15%**	**20%**
Car - No TSP	20.30	21.93	23.73	25.69
Car - GE	20.22	21.82	23.65	25.58
Truck - No TSP	25.59	26.79	28.52	30.97
Truck - GE	25.46	26.62	28.71	30.60
Bus - No TSP	25.25	26.48	28.01	30.46
Bus - GE	25.34	26.56	28.19	29.67

10-Minute Bus Headway				
Scenario	**Truck Percentage**			
	5%	**10%**	**15%**	**20%**
Car - No TSP	19.87	21.25	23.05	25.16
Car - GE	19.90	21.36	23.19	25.16
Truck - No TSP	25.03	25.98	27.76	30.23
Truck - GE	24.93	26.10	27.86	30.23
Bus - No TSP	5.05	5.42	7.13	9.31
Bus - GE	4.97	5.52	7.02	8.68

15-Minute Bus Headway				
Scenario	**Truck Percentage**			
	5%	**10%**	**15%**	**20%**
Car - No TSP	19.88	21.31	23.37	25.20
Car - GE	19.91	21.34	23.17	25.13
Truck - No TSP	25.10	25.98	28.16	30.17
Truck - GE	25.11	26.11	27.71	29.96
Bus - No TSP	26.12	27.05	27.92	27.91
Bus - GE	26.10	27.08	27.88	27.99

Table 20 Vehicle Average Delay – NS – GE20 - Summary

5-Minute Bus Headway				
Scenario	Truck Percentage			
	5%	10%	15%	20%
Car - No TSP	20.30	21.93	23.73	25.69
Car - GE	20.23	21.87	23.61	25.70
Truck - No TSP	25.59	26.79	28.52	30.97
Truck - GE	25.54	26.64	28.57	31.02
Bus - No TSP	25.25	26.48	28.01	30.46
Bus - GE	25.14	26.73	28.15	30.62

10-Minute Bus Headway				
Scenario	Truck Percentage			
	5%	10%	15%	20%
Car - No TSP	19.87	21.25	23.05	25.16
Car - GE	19.87	21.27	23.16	24.93
Truck - No TSP	25.03	25.98	27.76	30.23
Truck - GE	24.94	25.97	27.88	30.15
Bus - No TSP	5.05	5.42	7.13	9.31
Bus - GE	4.94	5.37	7.12	8.08

15-Minute Bus Headway				
Scenario	Truck Percentage			
	5%	10%	15%	20%
Car - No TSP	19.88	21.31	23.37	25.20
Car - GE	19.92	21.25	23.15	25.09
Truck - No TSP	25.10	25.98	28.16	30.17
Truck - GE	25.14	25.92	27.69	29.95
Bus - No TSP	26.12	27.05	27.92	27.91
Bus - GE	26.08	27.04	27.91	27.88

Table 21 Vehicle Average Delay – NS – GE30 - Summary

5-Minute Bus Headway				
Scenario	**Truck Percentage**			
	5%	**10%**	**15%**	**20%**
Car - No TSP	20.30	21.93	23.73	25.69
Car - GE	20.17	21.90	23.70	25.62
Truck - No TSP	25.59	26.79	28.52	30.97
Truck - GE	25.42	26.58	28.64	30.97
Bus - No TSP	25.25	26.48	28.01	30.46
Bus - GE	25.21	26.76	28.30	29.27

10-Minute Bus Headway				
Scenario	**Truck Percentage**			
	5%	**10%**	**15%**	**20%**
Car - No TSP	19.87	21.25	23.05	25.16
Car - GE	19.82	21.30	23.01	25.00
Truck - No TSP	25.03	25.98	27.76	30.23
Truck - GE	24.91	26.04	27.70	30.20
Bus - No TSP	5.05	5.42	7.13	9.31
Bus - GE	5.05	5.49	7.21	8.11

15-Minute Bus Headway				
Scenario	**Truck Percentage**			
	5%	**10%**	**15%**	**20%**
Car - No TSP	19.88	21.31	23.37	25.20
Car - GE	19.85	21.28	24.35	24.87
Truck - No TSP	25.10	25.98	28.16	30.17
Truck - GE	25.08	25.92	32.81	30.13
Bus - No TSP	26.12	27.05	27.92	27.91
Bus - GE	26.16	27.04	28.00	27.58

4.2 Over-Saturated Intersection

4.2.1 Near-Side Bus Location

For the oversaturated scenario, an overall intersection v/c ratio of 1.00 was used in Synchro and signal timing plans (shown previously in Figure 5) were obtained accordingly. Using the GEH analysis, it was noted at for the 20% truck percentage scenario, not all movements were able to meet the GEH requirement of five or less, and, therefore the 20% truck percentage scenario was eliminated for the over-saturated intersection analysis.

The average vehicle delay (QJL-TS scenario) for each of the vehicle classes (cars, trucks, and buses) are shown in

Figure 20, Figure 21 and Figure 22 respectively.

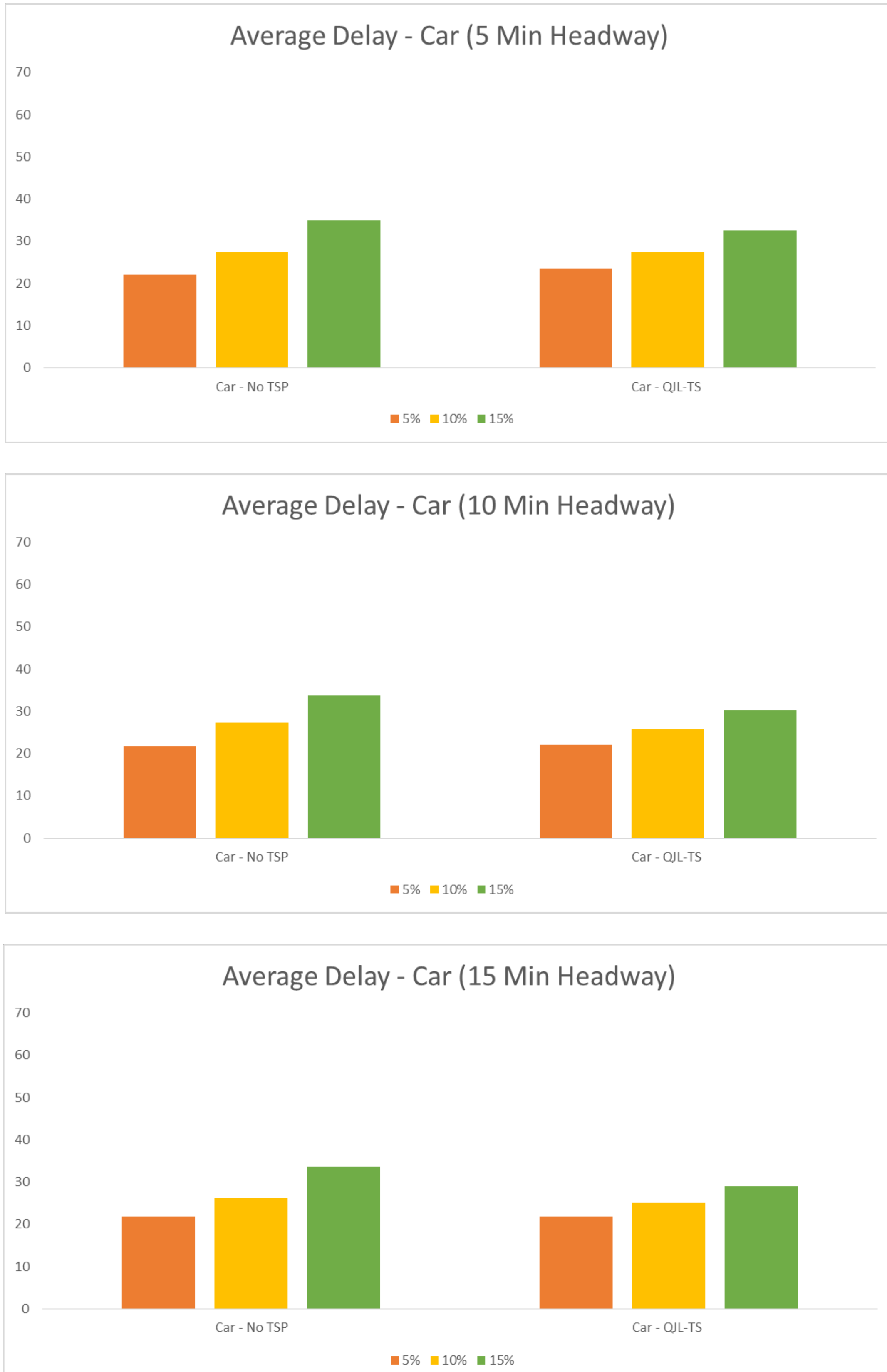
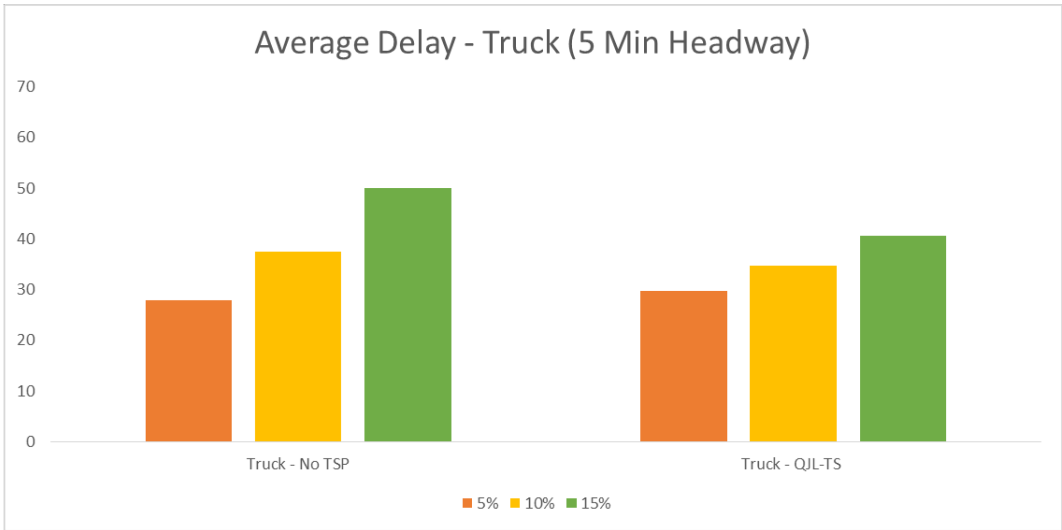
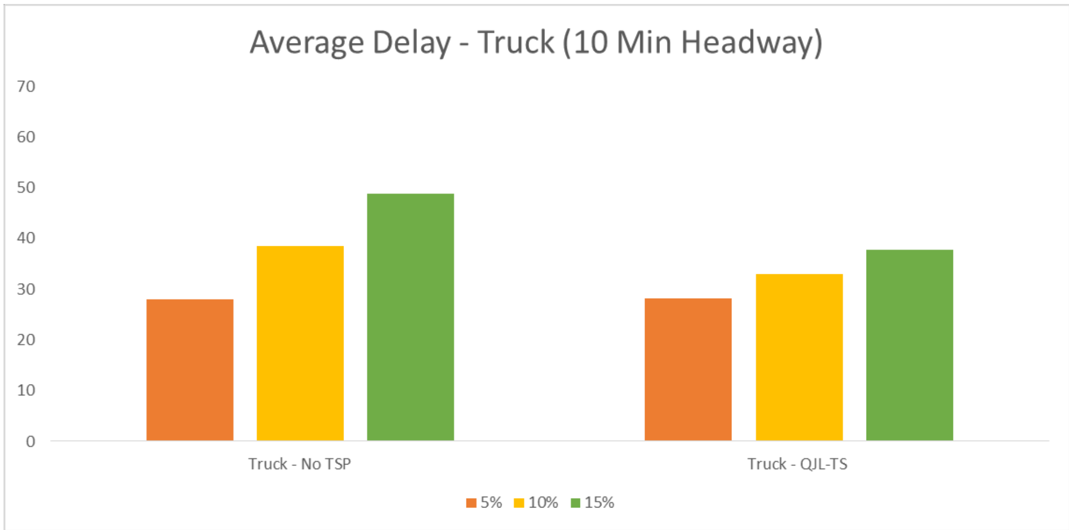


Figure 20 Average Vehicle (Car) Delay vs Truck Percentage – OS – QJL-TS





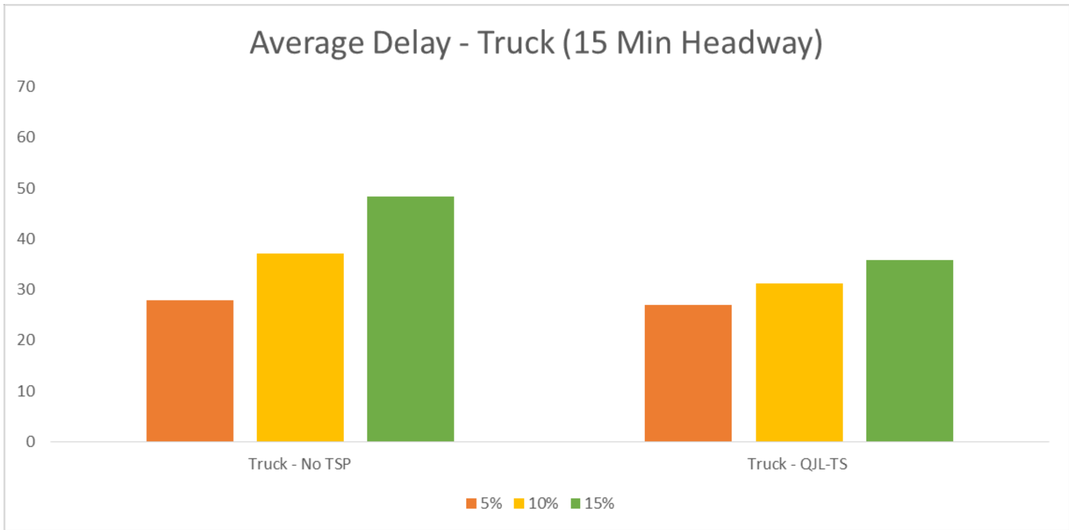
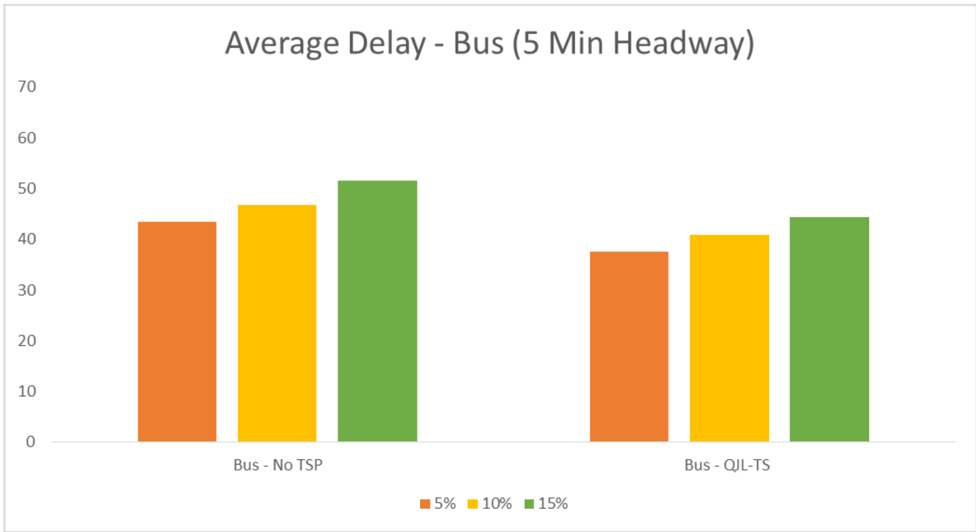
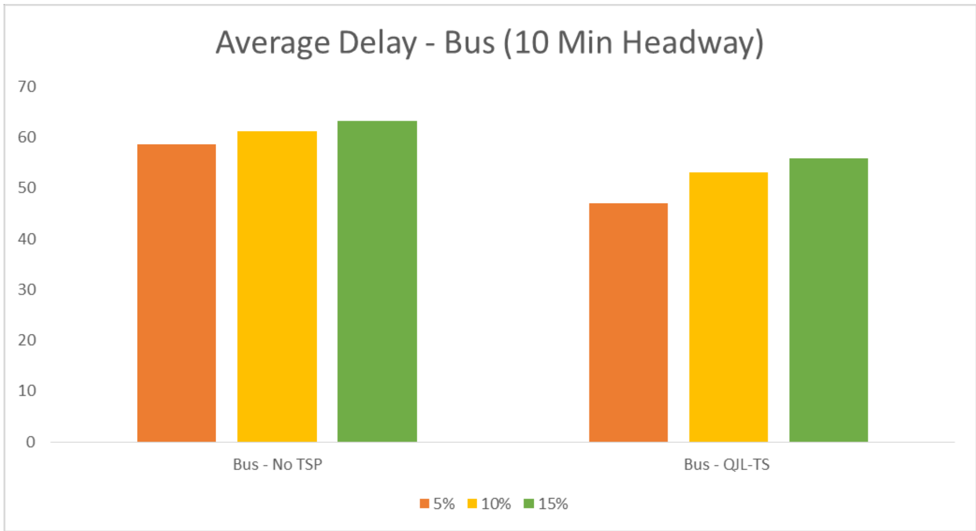


Figure 21 Average Vehicle (Truck) Delay vs Truck Percentage – OS – QJL-TS





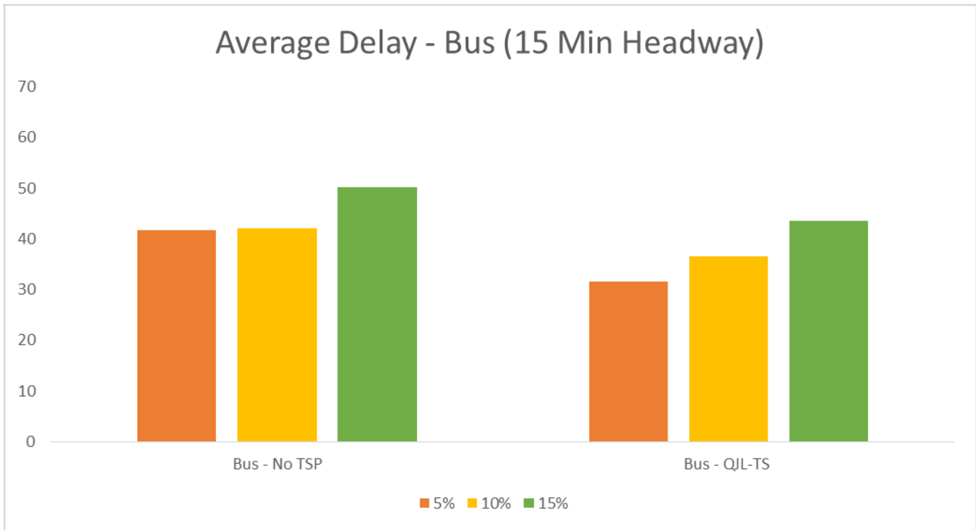


Figure 22 Average Vehicle (Bus) Delay vs Truck Percentage – OS – QJL-TS

The delay values obtained through the microsimulation analysis for the QJL-TS is shown in Table 22 below:

Table 22 Vehicle Average Delay – OS – QJL-TS - Summary

5-Minute Bus Headway			
Scenario	Truck Percentage		
	5%	10%	15%
Car - No TSP	21.97	27.32	34.94
Car - QJL-TS	23.54	27.33	32.47
Truck - No TSP	27.97	37.41	50.05
Truck - QJL-TS	29.80	34.67	40.64
Bus - No TSP	43.50	46.81	51.59
Bus - QJL-TS	37.51	40.78	44.33

10-Minute Bus Headway			
Scenario	Truck Percentage		
	5%	10%	15%
Car - No TSP	21.72	27.29	33.76
Car - QJL-TS	22.19	25.87	30.33
Truck - No TSP	28.04	38.46	48.87
Truck - QJL-TS	28.19	32.95	37.69
Bus - No TSP	58.70	61.25	63.23
Bus - QJL-TS	46.95	53.06	55.83

15-Minute Bus Headway			
Scenario	Truck Percentage		
	5%	10%	15%
Car - No TSP	21.76	26.19	33.65
Car - QJL-TS	21.82	25.12	29.04
Truck - No TSP	27.98	37.09	48.41
Truck - QJL-TS	27.01	31.19	35.82
Bus - No TSP	41.68	42.16	50.13
Bus - QJL-TS	31.53	36.58	43.55

Based on the results shown, it can be concluded that the implementation of QJL-TSP strategy for at a near-saturated intersection resulted in approximately 15% decrease in bus delay with the highest benefit observed for the 5% truck percentage (15 minute headway). Compared to the near-saturated intersection, this scenario provides a higher benefit to buses.

The average vehicle delay (GE scenario – 10 seconds) for each of the vehicle classes (cars, trucks, and buses) are shown in Figure 23, Figure 24 and Figure 25 respectively.

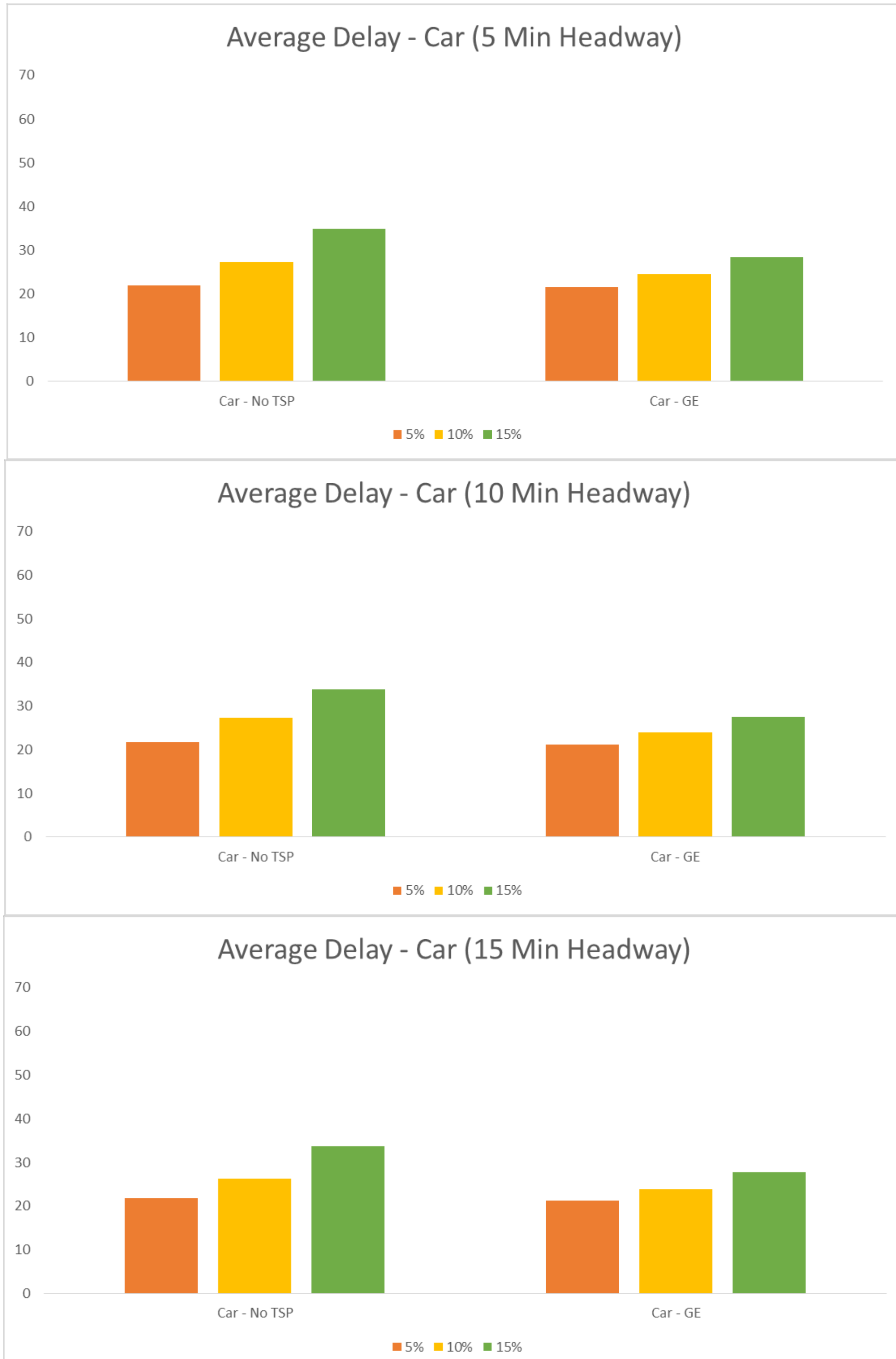


Figure 23 Average Vehicle (Car) Delay vs Truck Percentage – OS – GE10

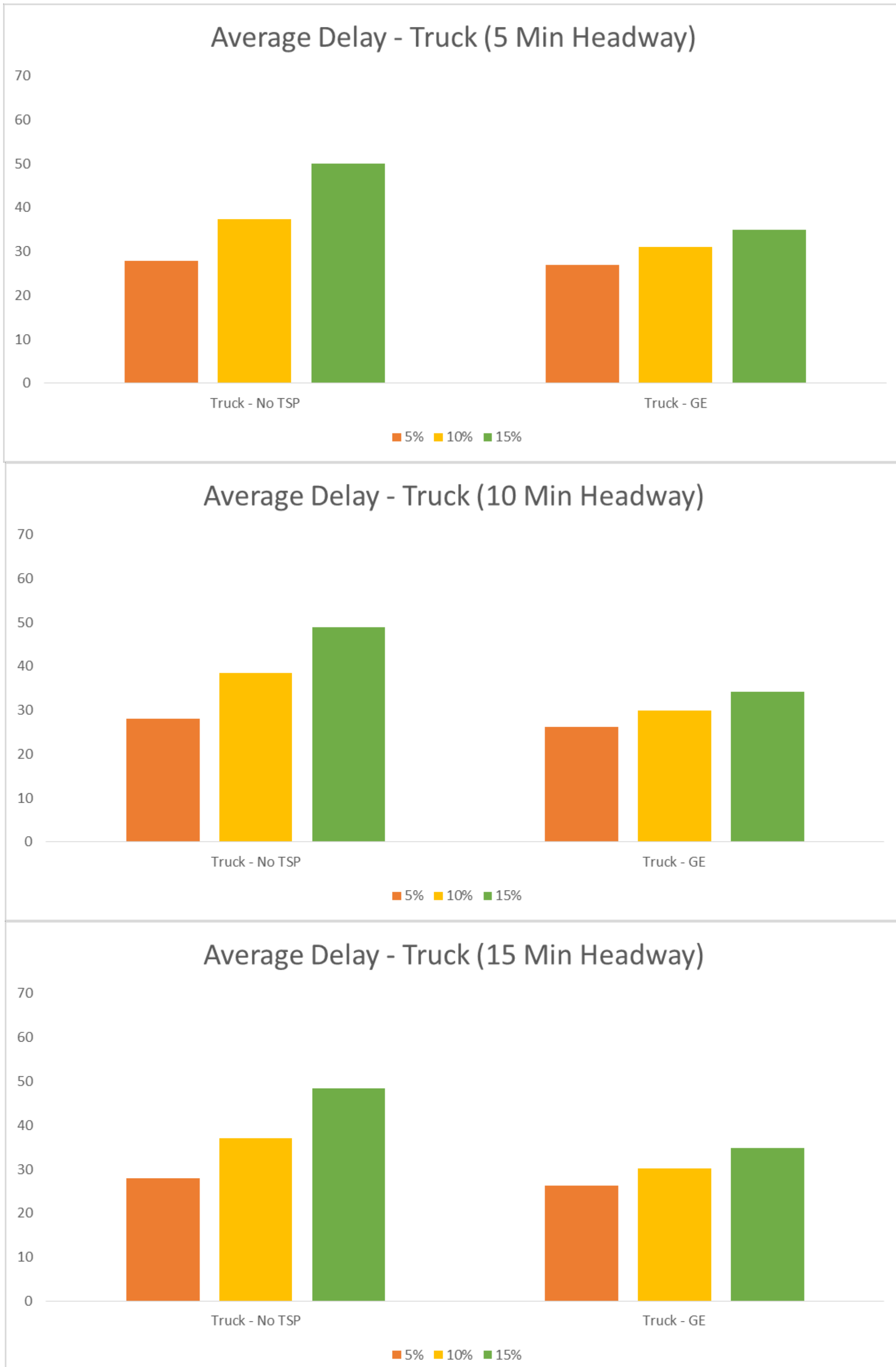


Figure 24 Average Vehicle (Truck) Delay vs Truck Percentage – OS – GE10

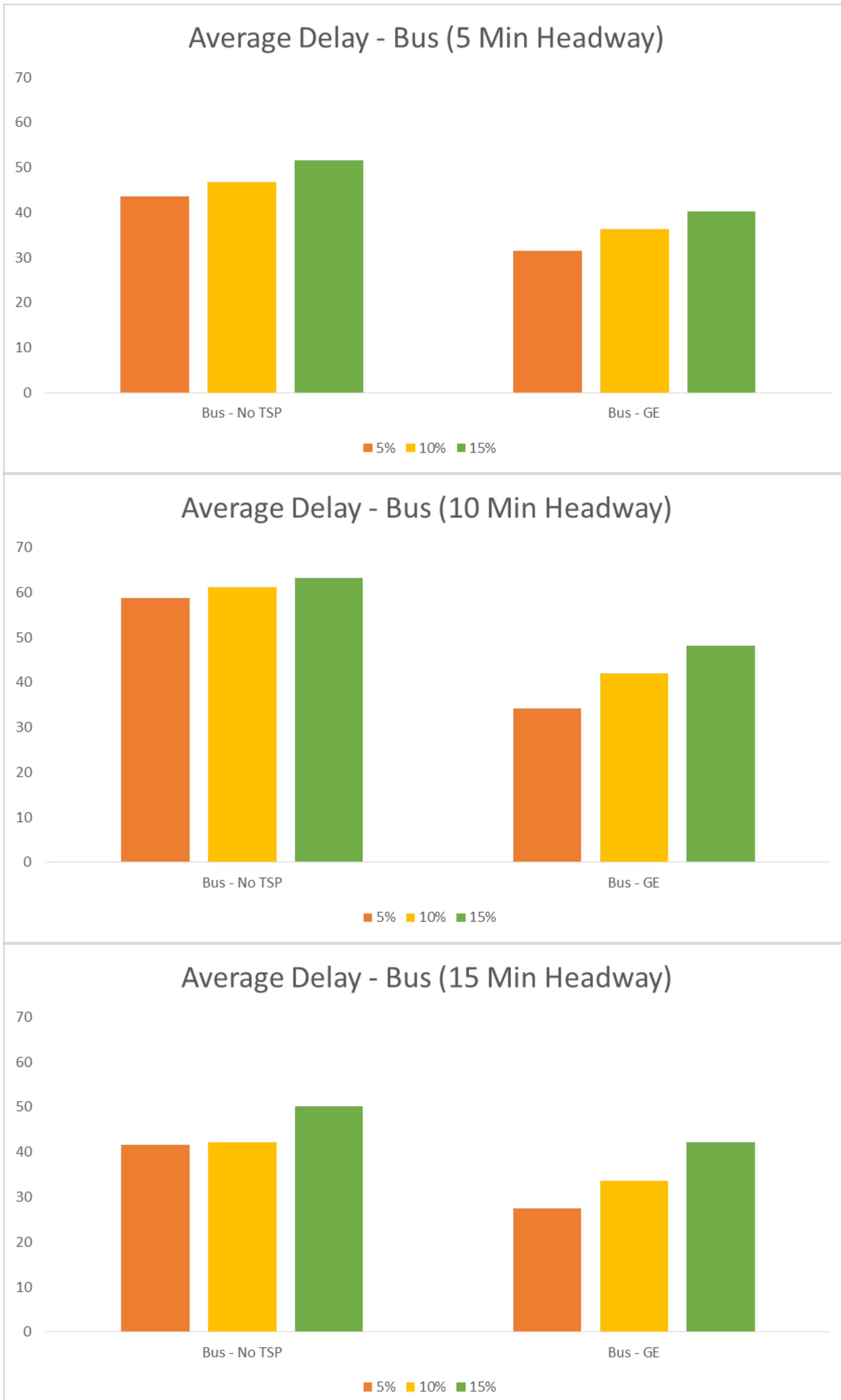


Figure 25 Average Vehicle (Bus) Delay vs Truck Percentage – OS – GE10

The delay values obtained through the microsimulation analysis for the GE scenario – 10 seconds is shown in Table 23 below:

Table 23 Vehicle Average Delay – OS – GE10 - Summary

5-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	21.97	27.32	34.94
Car - GE	21.56	24.48	28.31
Truck - No TSP	27.97	37.41	50.05
Truck - GE	27.01	30.98	35.04
Bus - No TSP	43.50	46.81	51.59
Bus - GE	31.55	36.29	40.22

10-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	21.72	27.29	33.76
Car - GE	21.21	23.97	27.58
Truck - No TSP	28.04	38.46	48.87
Truck - GE	26.20	30.00	34.09
Bus - No TSP	58.70	61.25	63.23
Bus - GE	34.25	42.10	48.15

15-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	21.76	26.19	33.65
Car - GE	21.24	23.92	27.77
Truck - No TSP	27.98	37.09	48.41
Truck - GE	26.36	30.11	34.77
Bus - No TSP	41.68	42.16	50.13
Bus - GE	27.54	33.63	42.18

The results shown above indicate an average of 27% decrease in bus delay with the highest benefit observed during the 5% truck percentage analysis (10 minute bus headway). Compared to the near-saturated intersection, Green Extension TSP provides less benefit to transit.

The average vehicle delay (GE scenario – 20 seconds) for each of the vehicle classes (cars, trucks, and buses) are shown in Figure 26, Figure 27 and Figure 28 respectively.

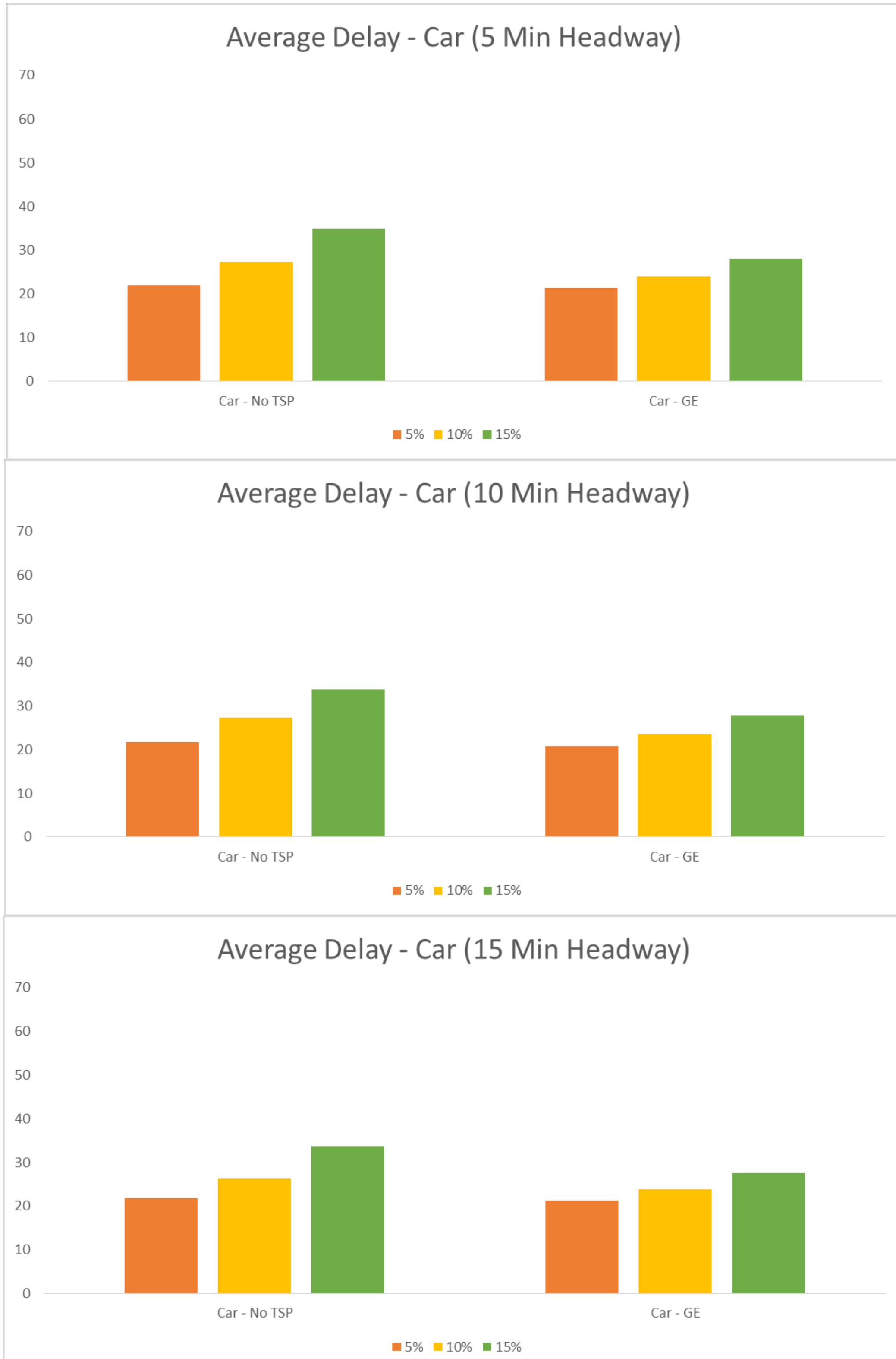


Figure 26 Average Vehicle (Car) Delay vs Truck Percentage – OS – GE20

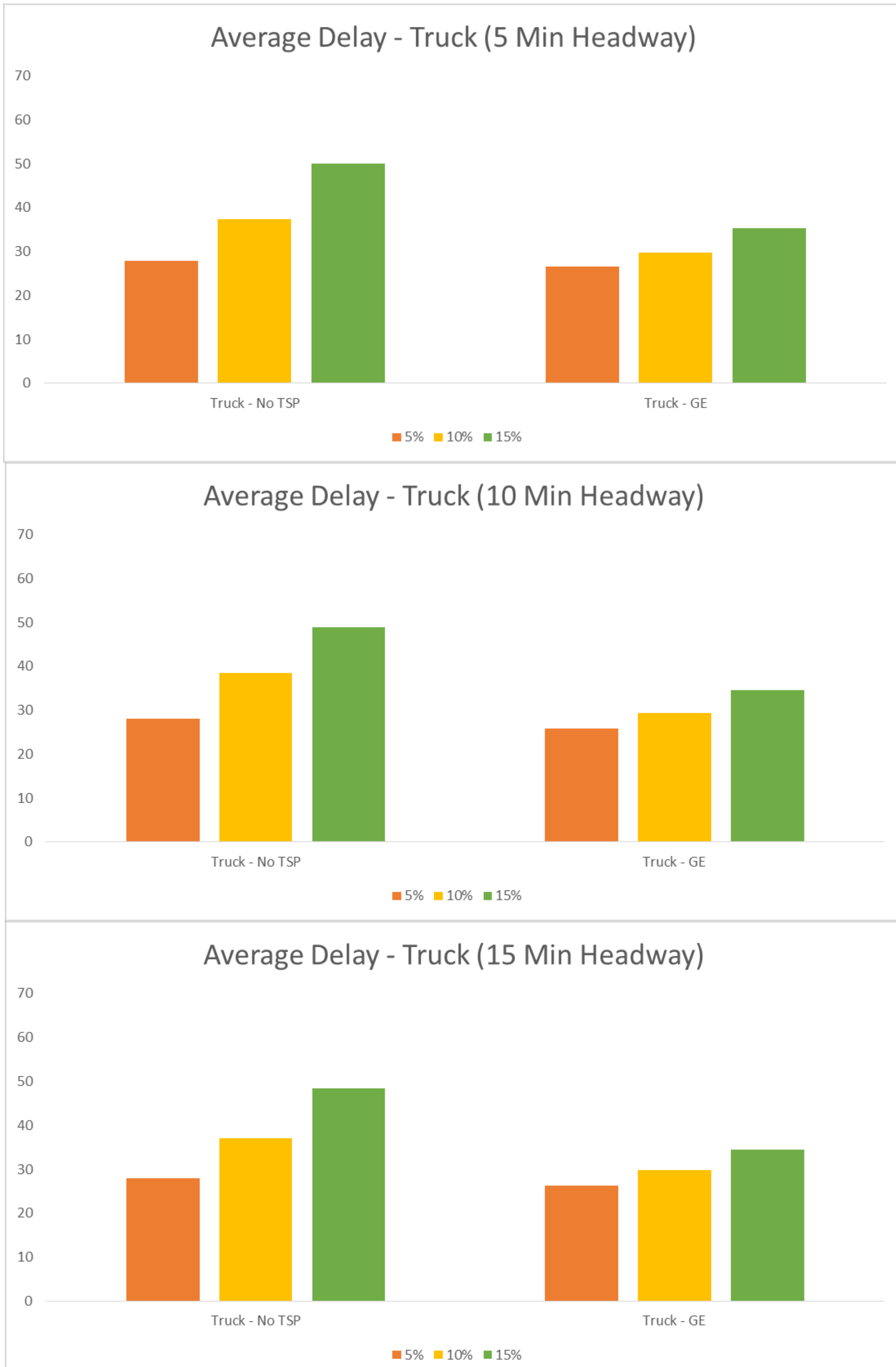


Figure 27 Average Vehicle (Truck) Delay vs Truck Percentage – OS – GE20

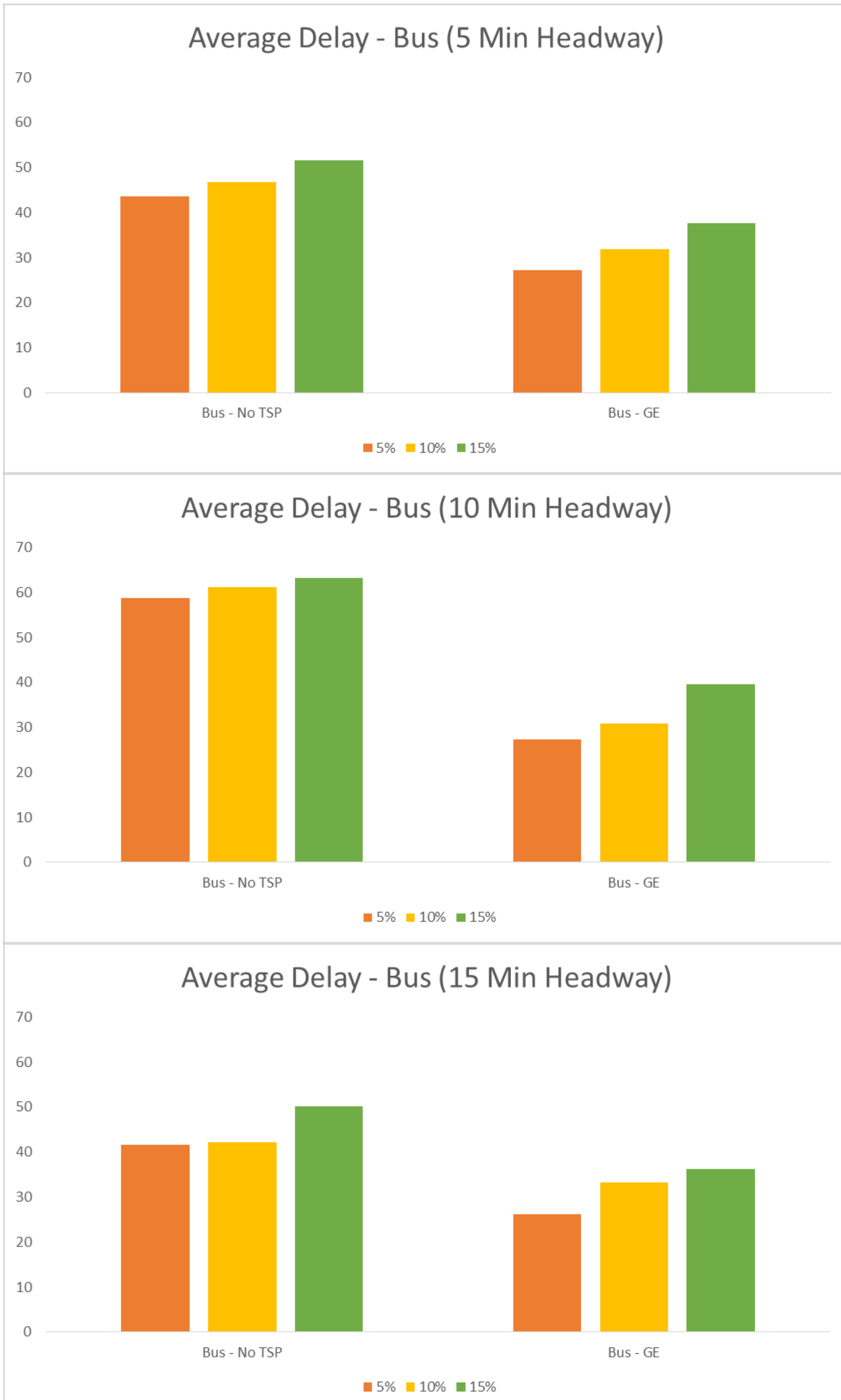


Figure 28 Average Vehicle (Bus) Delay vs Truck Percentage – OS – GE20

The delay values obtained through the microsimulation analysis for the GE scenario – 20 seconds is shown in Table 24 below:

Table 24 Vehicle Average Delay – OS – GE20 - Summary

5-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	21.97	27.32	34.94
Car - GE	21.32	23.98	27.99
Truck - No TSP	27.97	37.41	50.05
Truck - GE	26.62	29.70	35.36
Bus - No TSP	43.50	46.81	51.59
Bus - GE	27.14	31.92	37.59

10-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	21.72	27.29	33.76
Car - GE	20.87	23.56	27.83
Truck - No TSP	28.04	38.46	48.87
Truck - GE	25.90	29.28	34.58
Bus - No TSP	58.70	61.25	63.23
Bus - GE	27.25	30.82	39.69

15-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	21.76	26.19	33.65
Car - GE	21.20	23.80	27.59
Truck - No TSP	27.98	37.09	48.41
Truck - GE	26.23	29.84	34.45
Bus - No TSP	41.68	42.16	50.13
Bus - GE	26.16	33.28	36.19

The results for the GE scenario – 20 seconds indicate an average decrease of 36% in bus delay with the highest benefit observed during the 5% truck percentage (10 minute bus headway) analysis.

The average vehicle delay (GE scenario – 30 seconds) for each of the vehicle classes (cars, trucks, and buses) are shown in Figure 29, Figure 30 and Figure 31 respectively.

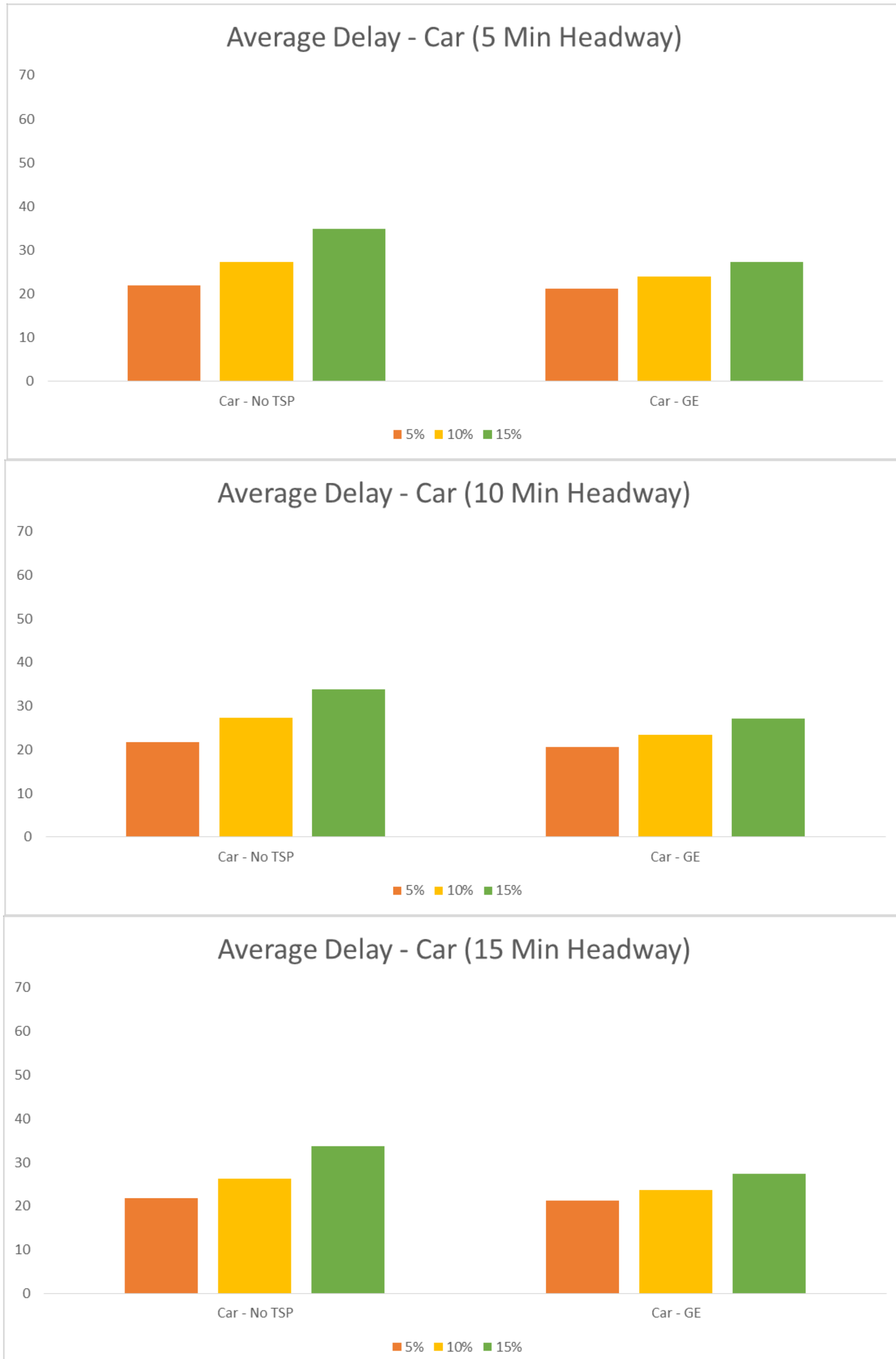


Figure 29 Average Vehicle (Car) Delay vs Truck Percentage – OS – GE30

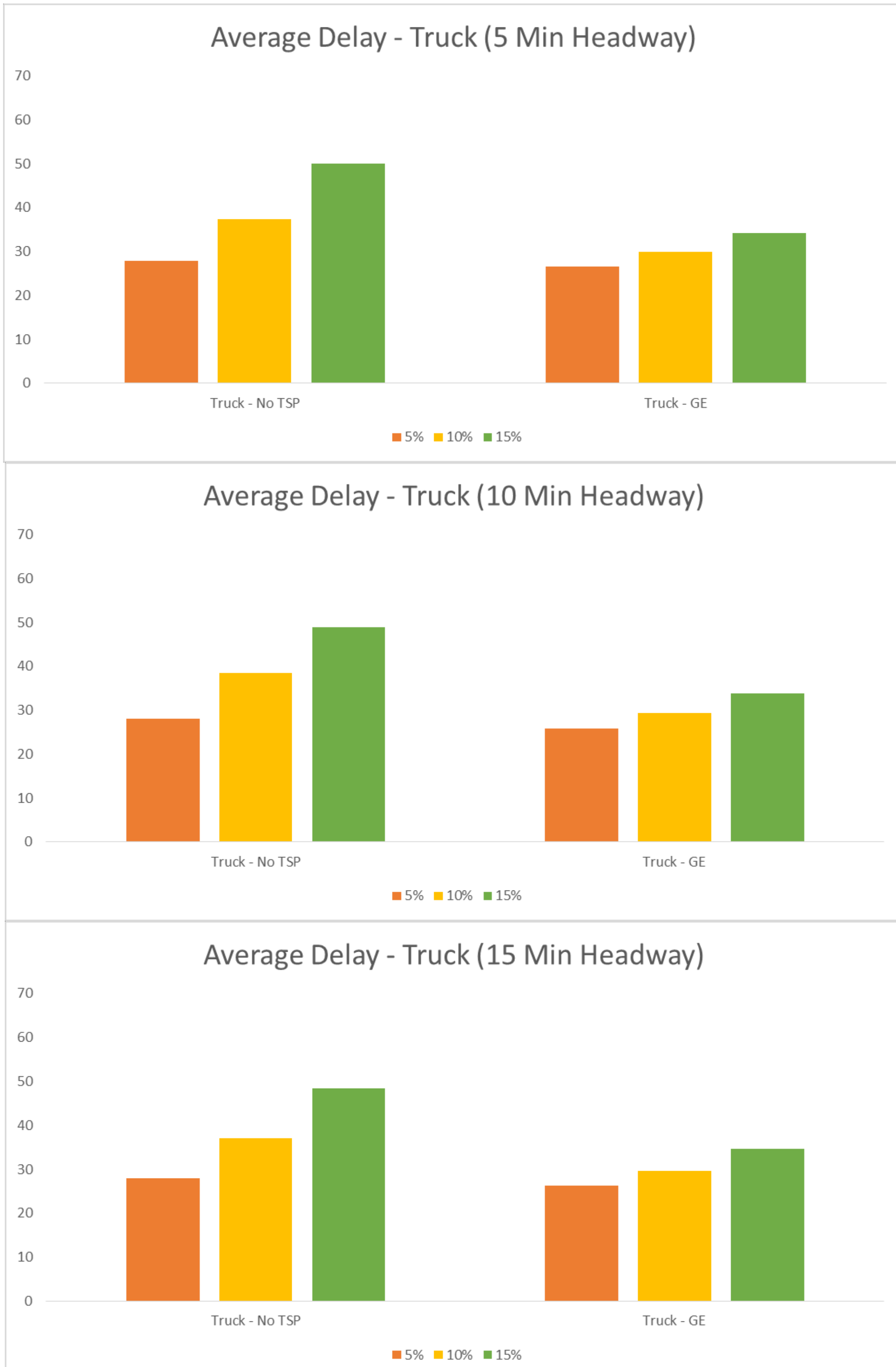


Figure 30 Average Vehicle (Truck) Delay vs Truck Percentage – OS – GE30

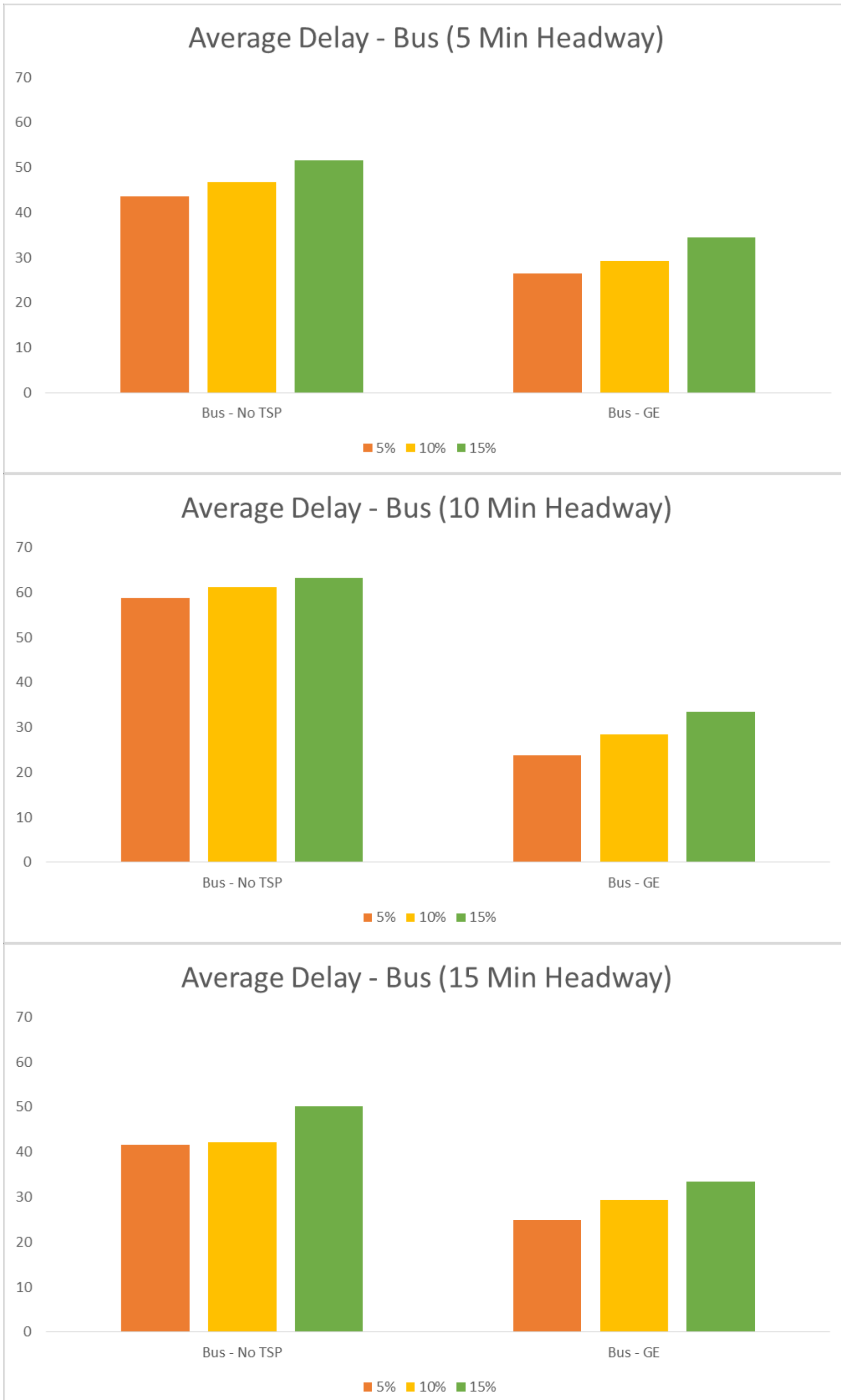


Figure 31 Average Vehicle (Bus) Delay vs Truck Percentage – OS – GE30

The delay values obtained through the microsimulation analysis for the GE scenario – 30 seconds is shown in Table 25 below:

Table 25 Vehicle Average Delay – OS – GE30 - Summary

5-Minute Bus Headway			
Scenario	Truck Percentage		
	5%	10%	15%
Car - No TSP	21.97	27.32	34.94
Car - GE	21.15	23.94	27.38
Truck - No TSP	27.97	37.41	50.05
Truck - GE	26.60	29.85	34.19
Bus - No TSP	43.50	46.81	51.59
Bus - GE	26.45	29.36	34.47

10-Minute Bus Headway			
Scenario	Truck Percentage		
	5%	10%	15%
Car - No TSP	21.72	27.29	33.76
Car - GE	20.72	23.42	27.16
Truck - No TSP	28.04	38.46	48.87
Truck - GE	25.83	29.35	33.78
Bus - No TSP	58.70	61.25	63.23
Bus - GE	23.88	28.42	33.47

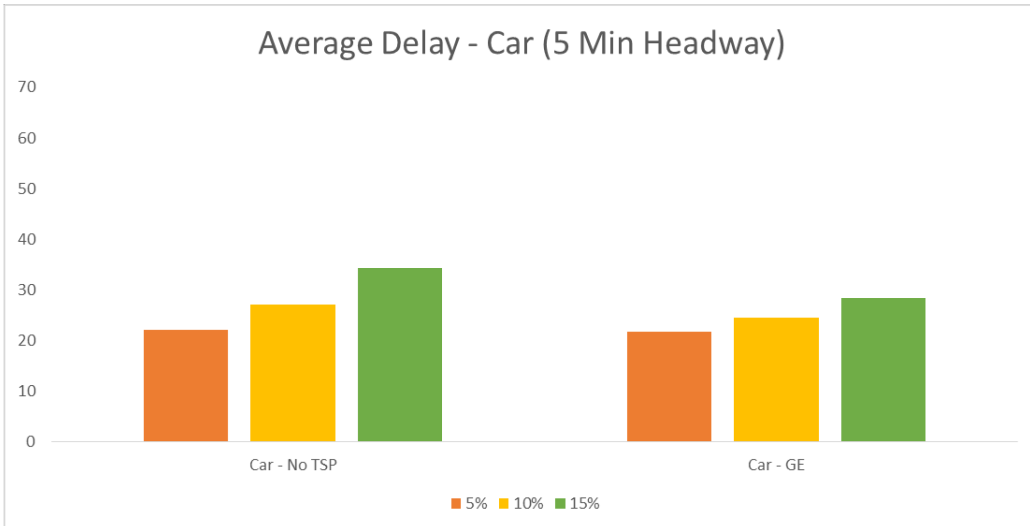
15-Minute Bus Headway			
Scenario	Truck Percentage		
	5%	10%	15%
Car - No TSP	21.76	26.19	33.65
Car - GE	21.19	23.63	27.45
Truck - No TSP	27.98	37.09	48.41
Truck - GE	26.26	29.65	34.65
Bus - No TSP	41.68	42.16	50.13
Bus - GE	24.84	29.37	33.34

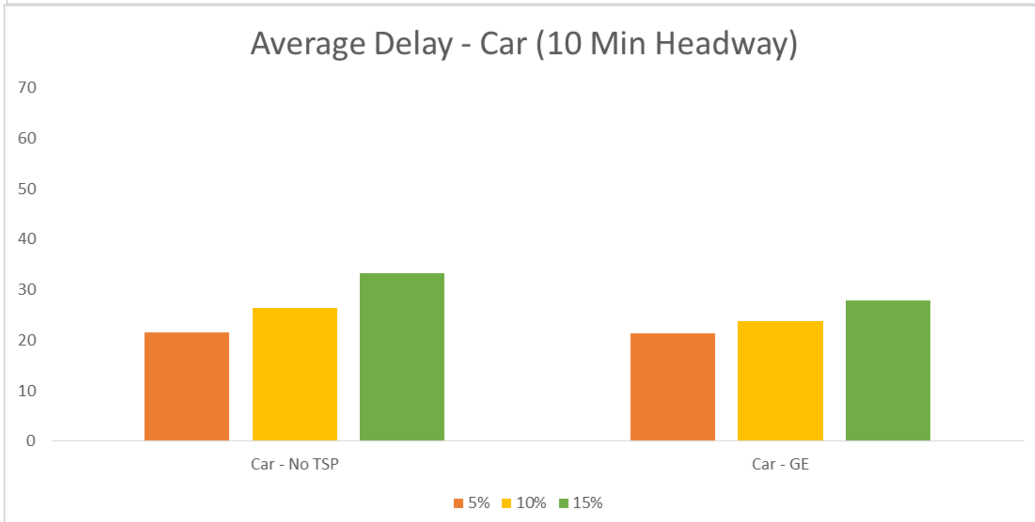
Based on the results shown, the GE – 30 seconds scenario provides an average of 42% decrease in delay for buses with the highest benefit observed during the 5% truck percentage (10 minute bus headway) analysis.

4.2.2 Far-Side Bus Location

For the far-side bus location scenario, the buses at the over-saturated intersection benefit from the provision of the Green Extension TSP compared to the near-saturated intersection scenario.

The average vehicle delay (GE scenario – 10 seconds) for each of the vehicle classes (cars, trucks, and buses) are shown in Figure 32, Figure 33 and Figure 34 respectively.





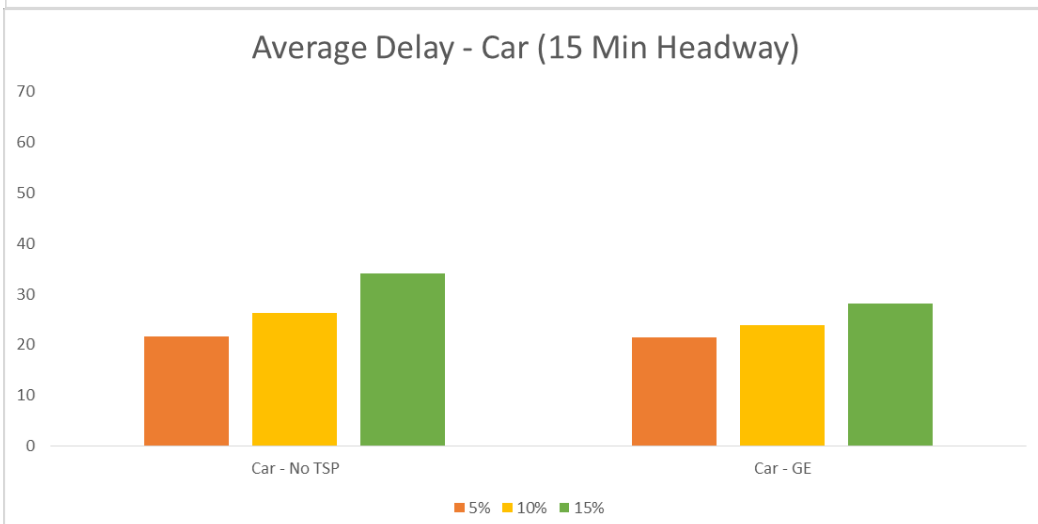


Figure 32 Average Vehicle (Car) Delay vs Truck Percentage – OS – FS - GE10

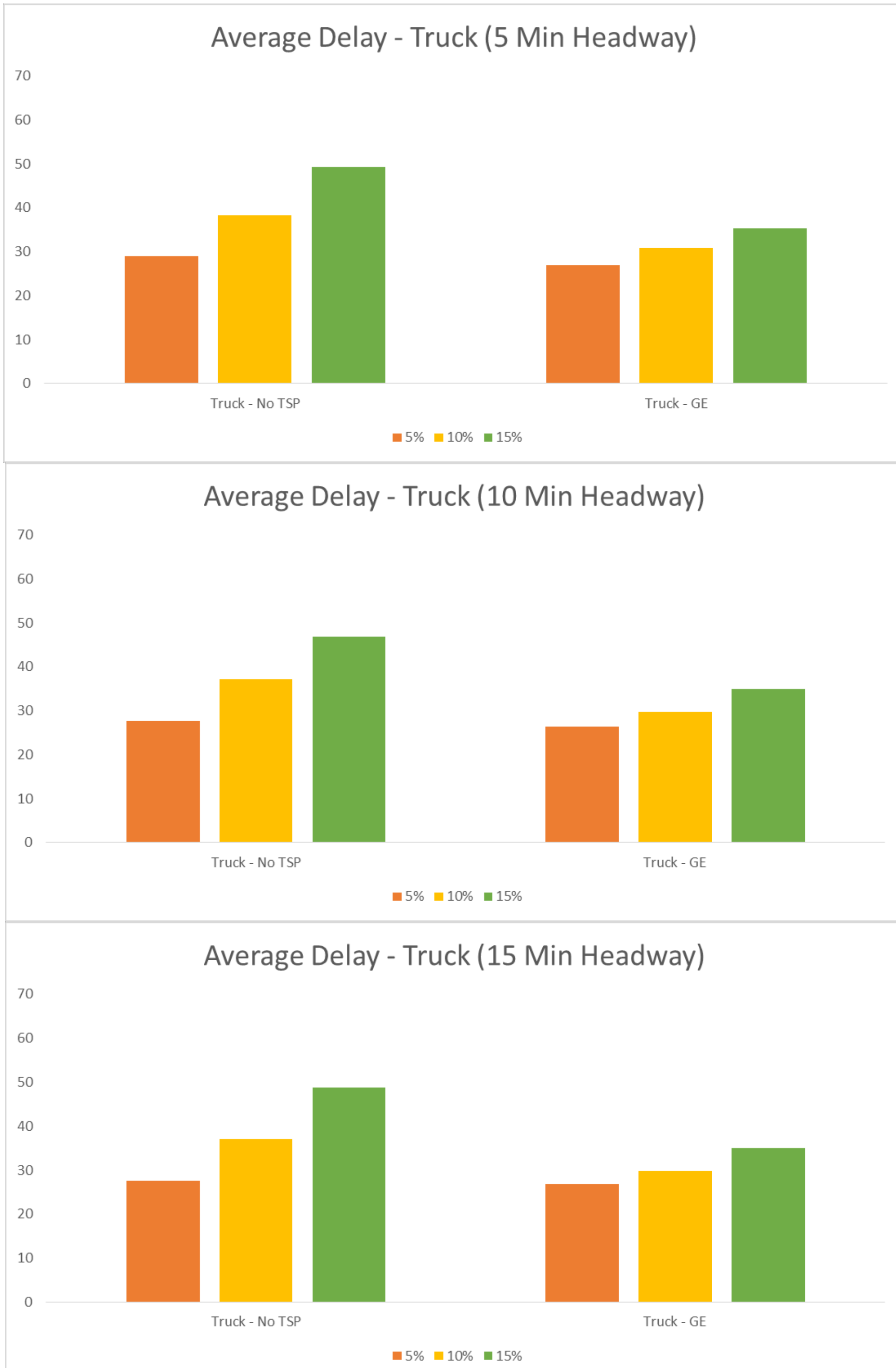


Figure 33 Average Vehicle (Truck) Delay vs Truck Percentage – OS – FS - GE10

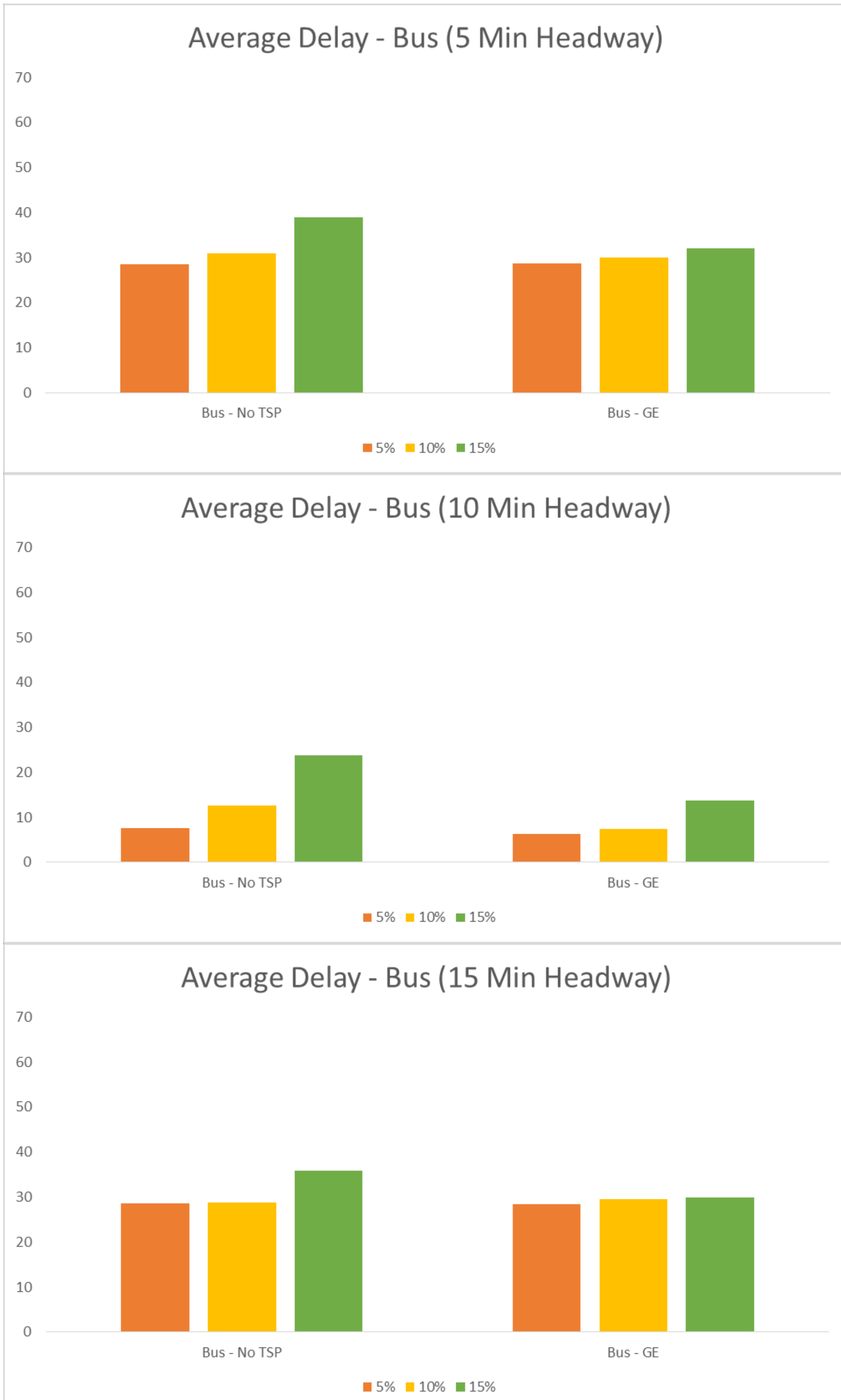


Figure 34 Average Vehicle (Bus) Delay vs Truck Percentage – OS – FS - GE10

The delay values obtained through the microsimulation analysis for the GE scenario – 10 seconds is shown in Table 26 below:

Table 26 Vehicle Average Delay – OS – FS – GE10 - Summary

5-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	22.07	27.11	34.26
Car - GE	21.76	24.52	28.46
Truck - No TSP	28.96	38.30	49.20
Truck - GE	26.91	30.90	35.31
Bus - No TSP	28.51	31.00	39.00
Bus - GE	28.69	30.05	32.01

10-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	21.53	26.41	33.26
Car - GE	21.31	23.78	27.92
Truck - No TSP	27.67	37.10	46.83
Truck - GE	26.35	29.77	34.85
Bus - No TSP	7.62	12.72	23.74
Bus - GE	6.39	7.48	13.80

15-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	21.70	26.23	34.09
Car - GE	21.35	23.79	28.09
Truck - No TSP	27.63	37.07	48.76
Truck - GE	26.78	29.75	35.01
Bus - No TSP	28.57	28.85	35.91
Bus - GE	28.37	29.59	29.95

The results shown in the figures and tables above for the GE – 10 seconds scenario illustrate an average of 15% decrease in delay for buses with the highest benefit observed during the 15% truck percentage (10 minute bus headway) analysis.

The average vehicle delay (GE scenario – 20 seconds) for each of the vehicle classes (cars, trucks, and buses) are shown in Figure 35, Figure 36, and Figure 37 respectively.

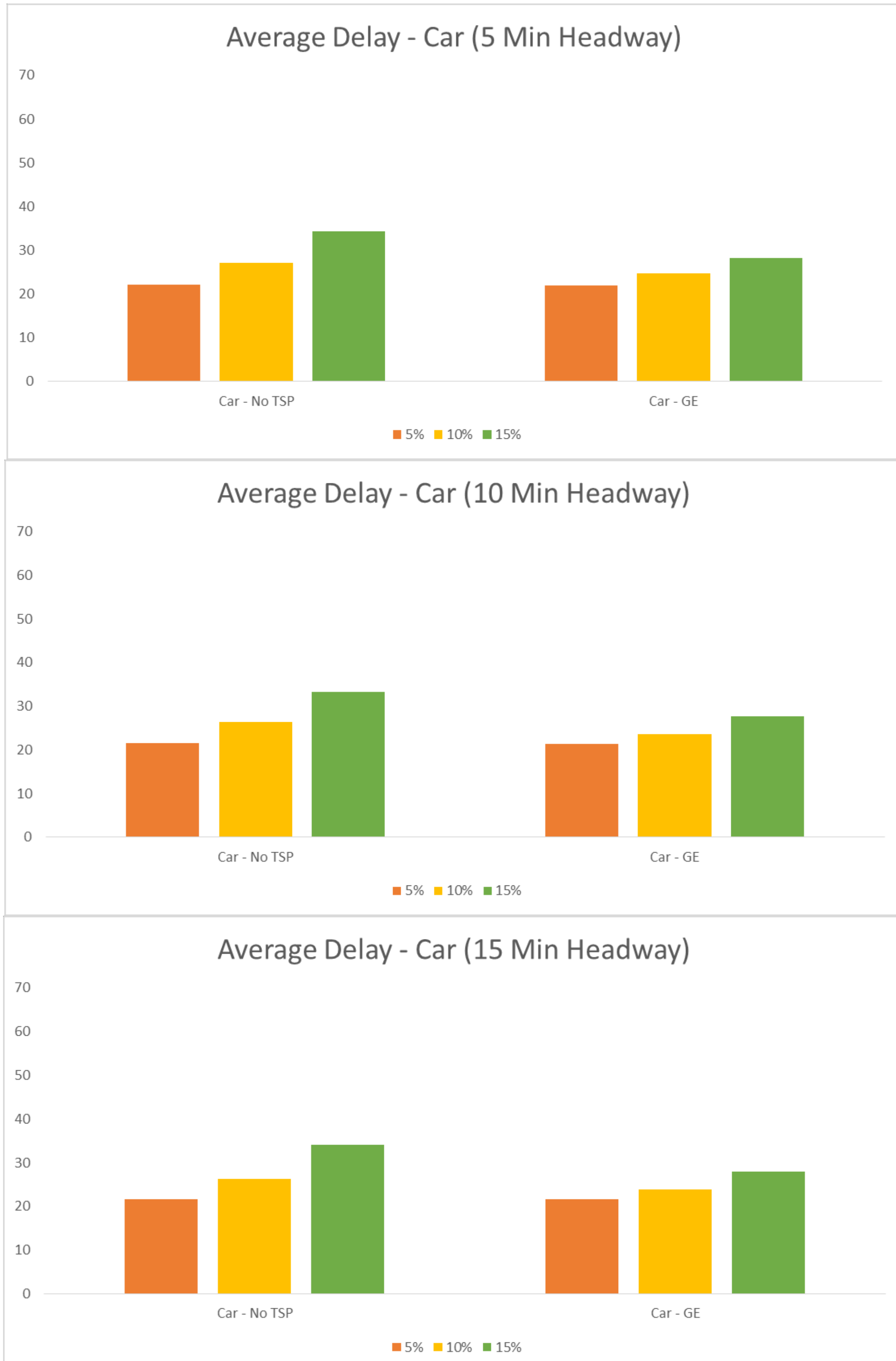


Figure 35 Average Vehicle (Car) Delay vs Truck Percentage – OS – FS – GE20

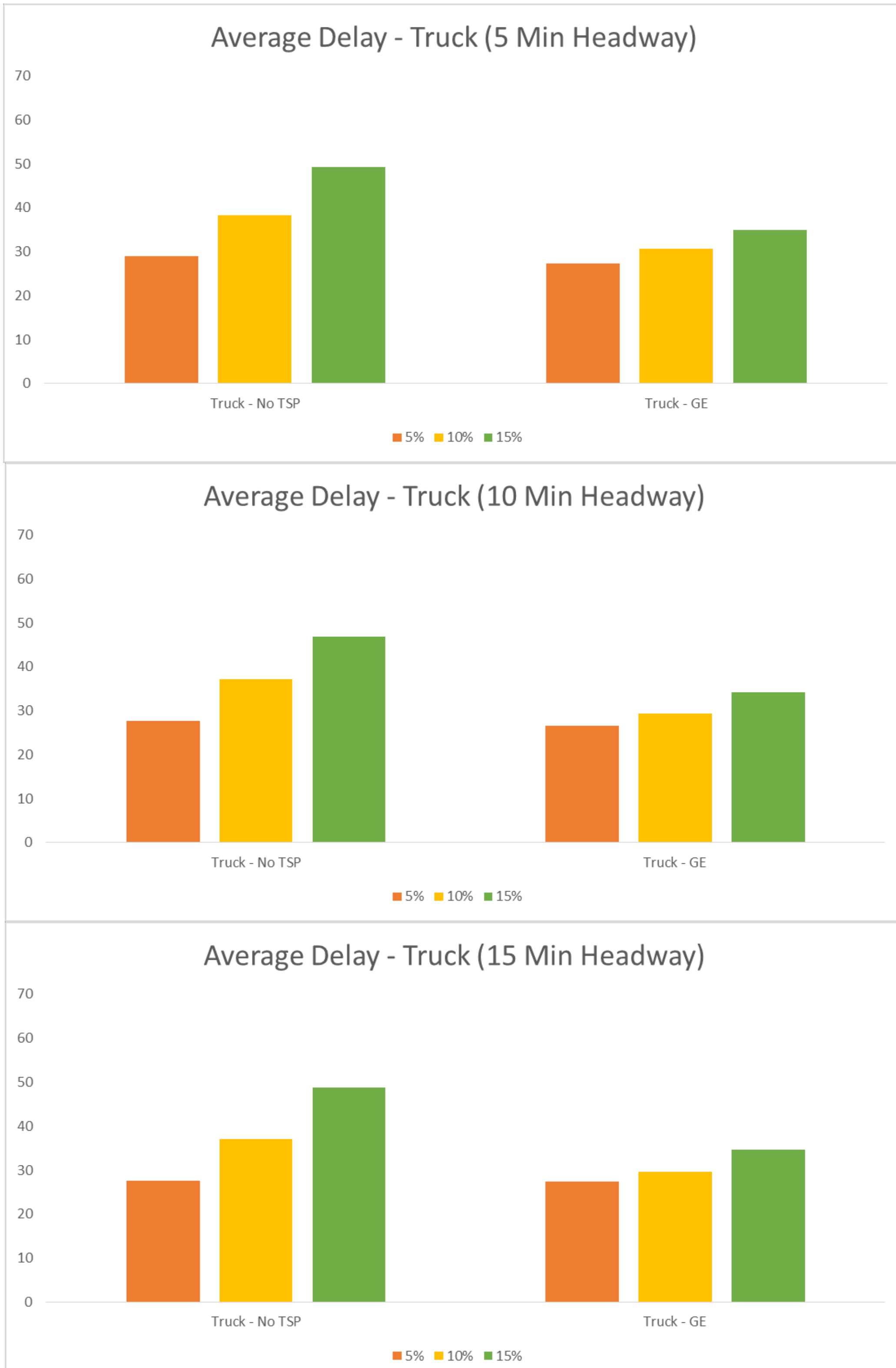


Figure 36 Average Vehicle (Truck) Delay vs Truck Percentage – OS – FS – GE20

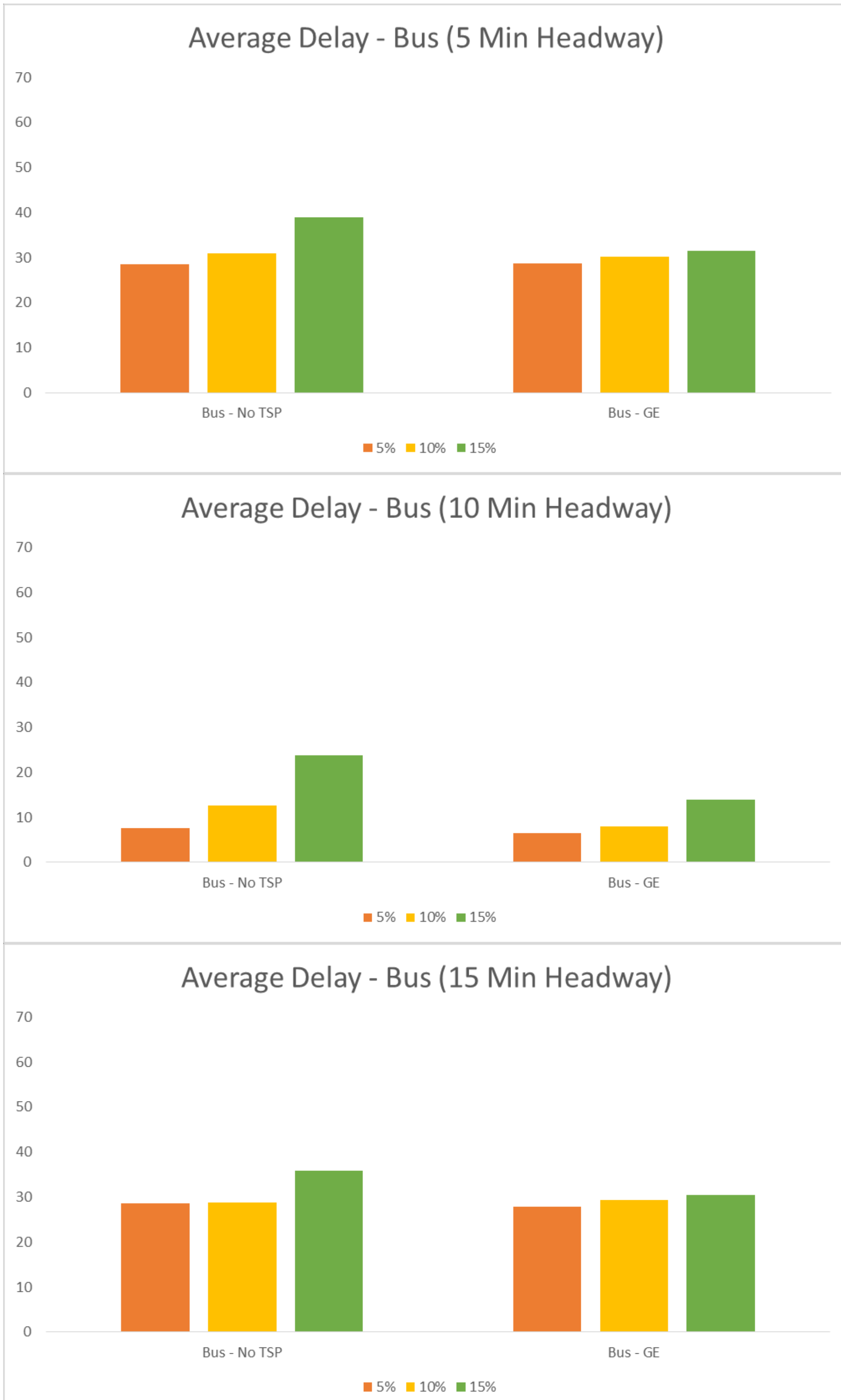


Figure 37 Average Vehicle (Bus) Delay vs Truck Percentage – OS – FS – GE20

The delay values obtained through the microsimulation analysis for the GE scenario – 20 seconds is shown in Table 27 below:

Table 27 Vehicle Average Delay – OS – FS – GE20 - Summary

5-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	22.07	27.11	34.26
Car - GE	21.91	24.64	28.17
Truck - No TSP	28.96	38.30	49.20
Truck - GE	27.29	30.62	34.89
Bus - No TSP	28.51	31.00	39.00
Bus - GE	28.68	30.18	31.49

10-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	21.53	26.41	33.26
Car - GE	21.30	23.65	27.62
Truck - No TSP	27.67	37.10	46.83
Truck - GE	26.51	29.43	34.26
Bus - No TSP	7.62	12.72	23.74
Bus - GE	6.56	7.90	13.95

15-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	21.70	26.23	34.09
Car - GE	21.61	23.79	27.92
Truck - No TSP	27.63	37.07	48.76
Truck - GE	27.48	29.68	34.61
Bus - No TSP	28.57	28.85	35.91
Bus - GE	27.89	29.41	30.51

The GE – 20 second scenario results shows similar decrease in delay as the GE – 10 second scenario with the highest benefit observed during the 15% truck percentage (10 minute headway) analysis.

The average vehicle delay (GE scenario – 30 seconds) for each of the vehicle classes (cars, trucks, and buses) are shown in Figure 38, Figure 39 and Figure 40 respectively.

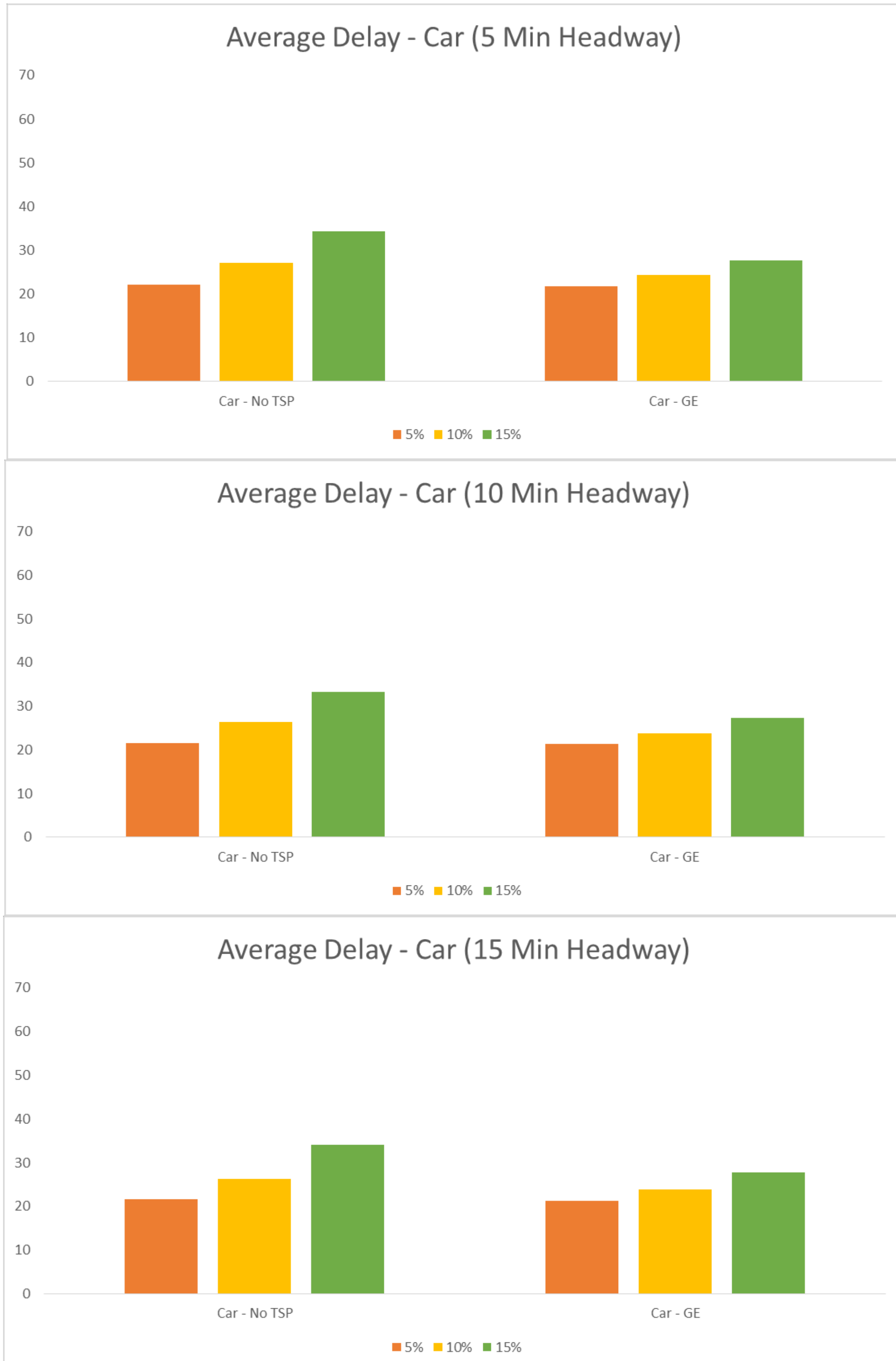


Figure 38 Average Vehicle (Car) Delay vs Truck Percentage – OS – FS – GE30

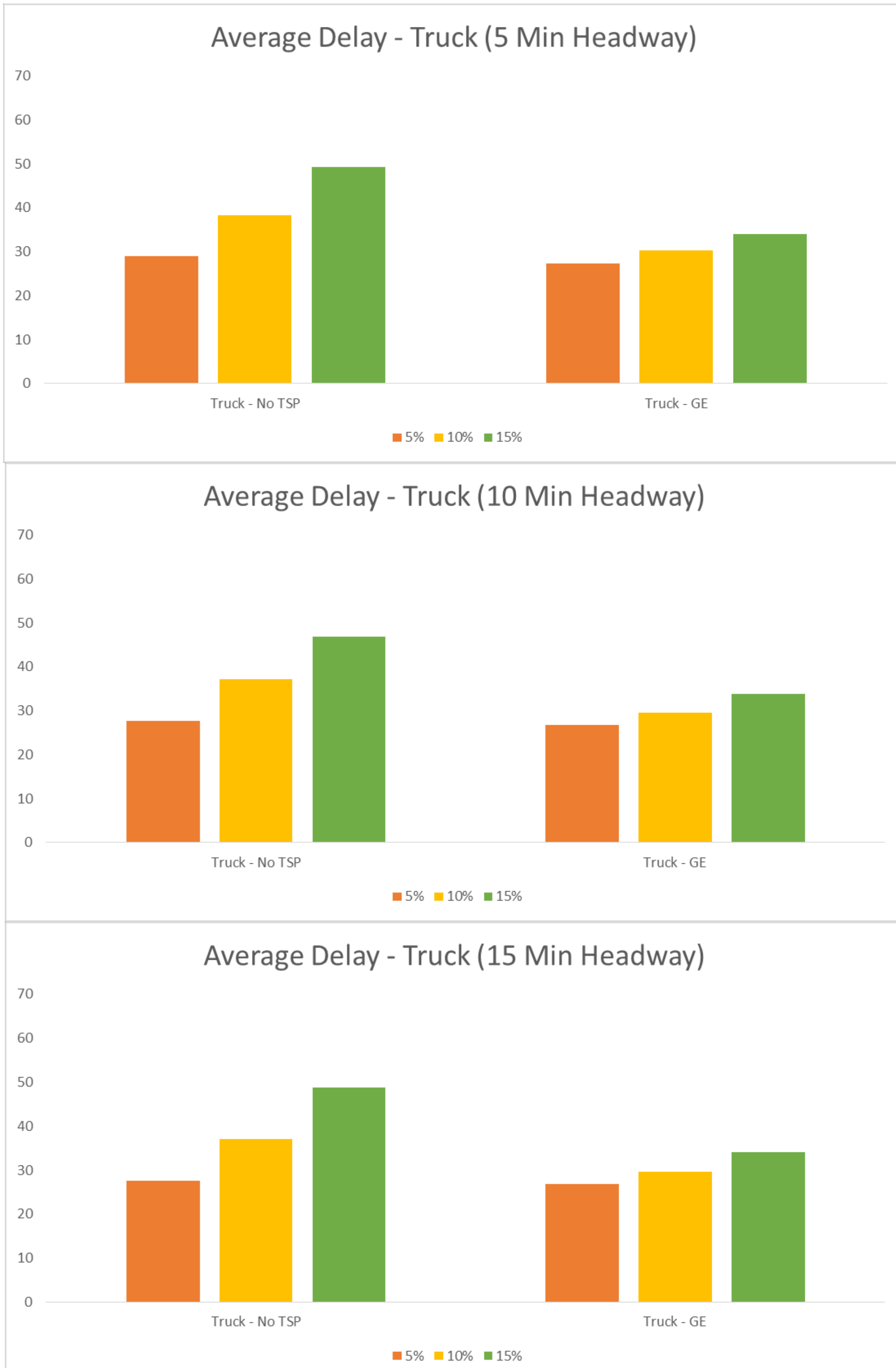


Figure 39 Average Vehicle (Truck) Delay vs Truck Percentage – OS – FS – GE30

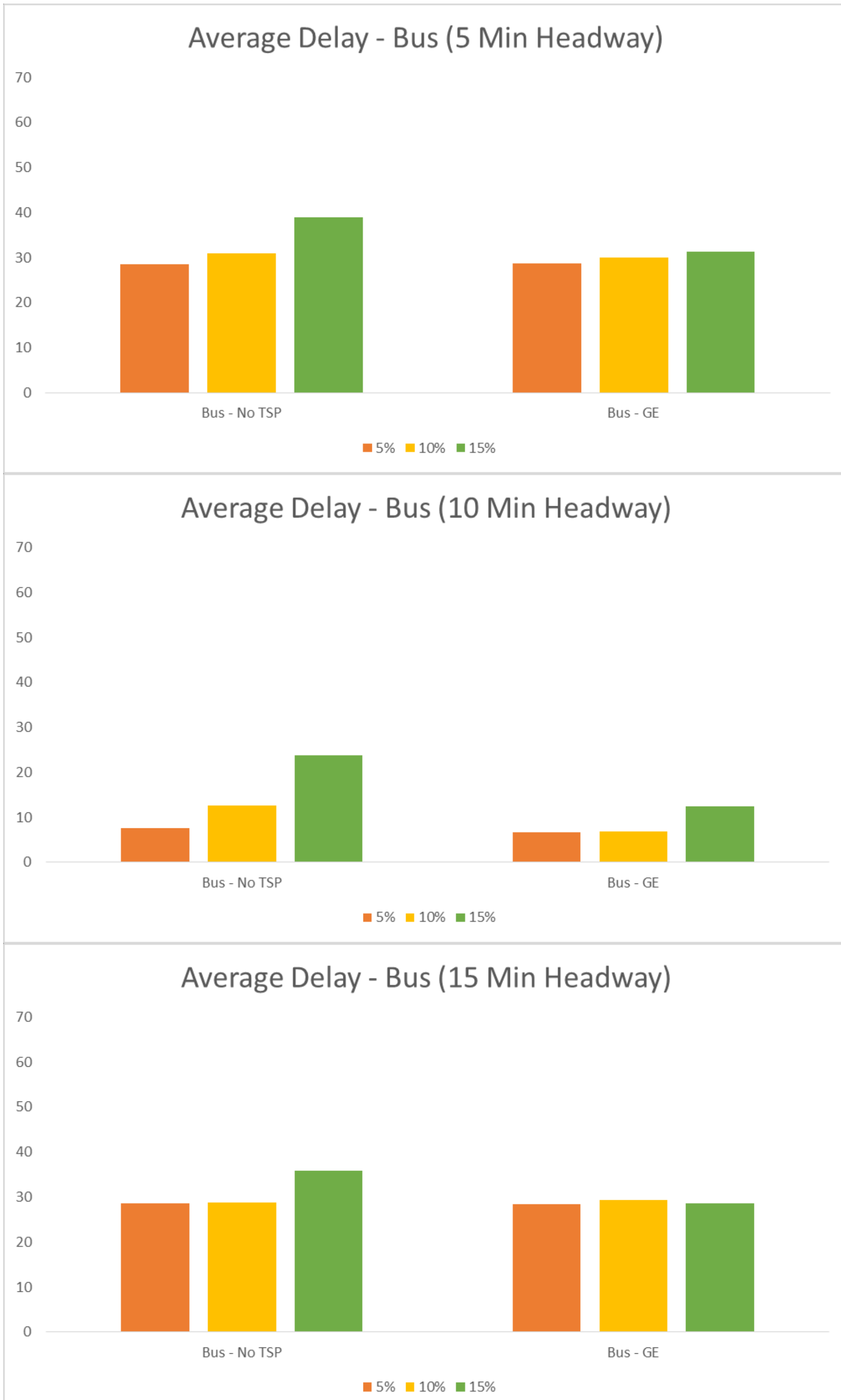


Figure 40 Average Vehicle (Bus) Delay vs Truck Percentage – OS – FS – GE30

The delay values obtained through the microsimulation analysis for the GE scenario – 30 seconds is shown in Table 28 below:

Table 28 Vehicle Average Delay – OS – FS – GE30 - Summary

5-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	22.07	27.11	34.26
Car - GE	21.75	24.27	27.64
Truck - No TSP	28.96	38.30	49.20
Truck - GE	27.32	30.25	33.97
Bus - No TSP	28.51	31.00	39.00
Bus - GE	28.65	29.98	31.29

10-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	21.53	26.41	33.26
Car - GE	21.31	23.81	27.37
Truck - No TSP	27.67	37.10	46.83
Truck - GE	26.74	29.44	33.88
Bus - No TSP	7.62	12.72	23.74
Bus - GE	6.61	6.80	12.53

15-Minute Bus Headway			
Scenario	**Truck Percentage**		
	5%	**10%**	**15%**
Car - No TSP	21.70	26.23	34.09
Car - GE	21.32	23.79	27.78
Truck - No TSP	27.63	37.07	48.76
Truck - GE	26.76	29.68	34.02
Bus - No TSP	28.57	28.85	35.91
Bus - GE	28.34	29.29	28.56

The results shown in the figures and tables above for the GE – 30 second scenario indicate an average decrease in bus delay of 17% with the highest benefit observed for the 10% and 15% truck percentage (10 minute bus headway) scenarios.

5. Conclusions and Future Work

5.1 Conclusions

Based on the results of the analysis, it can be concluded that the higher the truck percentage, the higher the delay experienced by all vehicles at the intersection. It was also observed that vehicles experienced a higher delay during over-saturated conditions as expected.

Table 29 and Table 30 illustrate a summary of the percentage decrease in delay experienced by buses for both near-saturated and over-saturated intersections:

Table 29 Percentage Decrease – Bus Delay - NS

TSP Strategy	**Near Saturated Intersection**	**Truck Percentage**			
	Bus Headway	**5%**	**10%**	**15%**	**20%**
QJL-TS	**5-Minute**	6%	4%	8%	5%
	10-Minute	2%	-7%	-6%	-2%
	15-Minute	1%	-2%	3%	9%
GE-10	**5-Minute**	40%	36%	35%	29%
	10-Minute	57%	56%	46%	43%
	15-Minute	34%	30%	36%	38%
GE-20	**5-Minute**	45%	43%	42%	41%
	10-Minute	65%	64%	61%	61%
	15-Minute	40%	37%	41%	45%
GE-30	**5-Minute**	45%	45%	45%	43%
	10-Minute	65%	64%	63%	63%
	15-Minute	40%	36%	41%	45%

Table 30 Percentage Decrease – Bus Delay - OS

TSP Strategy	**Over Saturated Intersection**	**Truck Percentage**			
	Bus Headway	**5%**	**10%**	**15%**	**20%**
QJL-TS	**5-Minute**	14%	13%	14%	
	10-Minute	20%	13%	12%	
	15-Minute	24%	13%	13%	
GE-10	**5-Minute**	27%	22%	22%	
	10-Minute	42%	31%	24%	
	15-Minute	34%	20%	16%	
GE-20	**5-Minute**	38%	32%	27%	
	10-Minute	54%	50%	37%	
	15-Minute	37%	21%	28%	
GE-30	**5-Minute**	39%	37%	33%	
	10-Minute	59%	54%	47%	
	15-Minute	40%	30%	33%	

As shown in the tables above, during the near-saturated traffic conditions, GE provides higher benefit compared to QJL-TS, with the highest benefit observed for the GE-30 seconds scenario. It was also noted that the TSP strategies were mainly effective for lower truck percentage levels (i.e. 5%) and less effective as truck percentages increase. QJL-TS scenario also showed more fluctuations in the results, as the TSP effectiveness highly depends on the arrival time of the buses at the intersection. As an example, during the 10-minute headway scenario simulation, buses arrive mid-cycle which is beneficial for the GE scenario, however, for the QJL-TS scenario, it may lead to an increase in their delay as they will not benefit from the advanced signal and right-of-way. The highest benefit was observed in the GE scenario for the 10 minute bus headway scenario due to the cycle length and arrival on green times, which highlights the importance of coordination at signalized intersections.

For the far-side location scenario, the highest truck percentage tested (20%) observed the highest benefit using GE TSP while the lowest (5% truck percentage) experienced no benefits.

For the over-saturated traffic conditions, GE provides higher benefit compared to QJL-TS. Similar to the near-saturated traffic conditions, it was observed that TSPs were beneficial for lower truck percentages traffic composition, i.e. 5% truck percentage.

For the far-side bus location scenario, the highest truck percentage tested (15%) observed the highest benefit using GE TSP.

5.2 Future Work

For future analysis, a combination of trucks, including small, medium, and heavy can be tested and analysis can be done to compare the effect of different combinations. It would also be beneficial to observe the impact on a corridor by measuring the effects of coordination between the signals on that corridor. Delay to other modes of transportation, such as pedestrians and cyclists at intersections and a warrant for heavy vehicle lanes and/or signals should also be further considered.

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