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# Environmental Impact of Freight Signal Priority with Connected Trucks

**Sangjun Park [1], Kyoungho Ahn [2,*] and Hesham A. Rakha [3]**

1 Department of Civil Engineering, Chosun University, Gwangju 61452, Korea; spark@chosun.ac.kr
2 Center for Sustainable Mobility, Virginia Tech Transportation Institute, Blacksburg, VA 24061, USA
3 The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech Transportation Institute, Blacksburg, VA 24060, USA; hrakha@vt.edu
* Correspondence: kahn@vt.edu; Tel.: +1-703-538-8447

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**Abstract:** Traffic signal priority is an operational technique employed for the smooth progression of a specific type of vehicle at signalized intersections. Transit signal priority is the most common type of traffic signal priority, and it has been researched extensively. Conversely, the impacts of freight signal priority (FSP) has not been widely investigated. Hence, this study aims to evaluate the energy and environmental impacts of FSP under connected vehicle environment by utilizing a simulation testbed developed for the multi-modal intelligent transportation signal system. The simulation platform consists of VISSIM microscopic traffic simulation software, a signal request messages distributor program, an RSE module, and an Econolite ASC/3 traffic controller emulator. The MOVES model was employed to estimate the vehicle fuel consumption and emissions. The simulation study revealed that the implementation of FSP significantly reduced the fuel consumption and emissions of connected trucks and general passenger cars; the network-wide fuel consumption was reduced by 11.8%, and the $CO_2$, HC, CO, and $NO_X$ emissions by 11.8%, 28.3%, 24.8%, and 25.9%, respectively. However, the fuel consumption and emissions of the side-street vehicles increased substantially due to the reduced green signal times on the side streets, especially in the high truck composition scenario.

**Keywords:** MMITSS; FSP; MOVES; environmental impacts; connected vehicles

## 1. Introduction

Traffic signal priority is an operational technique employed to ensure the smooth progression of a specific type of vehicle, such as a transit bus, an emergency vehicle, or a freight vehicle, at signalized intersections by retaining green signals or by shortening the time of red signals to have early green signals. A typical traffic signal priority system is composed of four functional components: Vehicle detection, priority request generation, priority request server, and traffic signal priority control [1]. The vehicle detection system is an essential component of an integrated system because the system accuracy is solely dependent upon the precision of the location and speed of the priority vehicle. According to the literature, two detection systems that have been widely implemented in the field are loop-based detection system and optical vehicle detection system. The recent advancements in the information and communication technology have resulted in the connected vehicle technologies, such as vehicle-to-vehicle and vehicle to infrastructure connections, which enable the implementation of a more enhanced traffic signal priority system.

Transit signal priority (TSP), which is the most common type of traffic signal priority, is implemented to enhance the operational performance of transit bus system, whereas freight signal priority (FSP) provides an early green or a green extension to freight vehicles for enhancing their performance and safety. Many studies have been conducted for the development, logic validation, and impact assessment of efficient TSP logics from the perspective of performance, whereas only a few studies have been performed to investigate the impacts of FSP.

In a study, He et al. proposed a priority traffic signal control system considering multiple modes such as transits, trucks, passenger cars, and pedestrians using a request-based mixed-integer linear program. From the simulation experiments, it was demonstrated that the proposed system can reduce the average delay of multiple modes, especially for highly congested conditions [2]. In another study, Mahmud evaluated the performance of an FSP system, which utilizes green time extension strategy using a loop detection method and NEMA signal controller in Verkehr In Städten – SIMulationsmodell(VISSIM), using VISSIM simulation software and verified that the travel delay and the stop delay were reduced by maximum 13% and 20%, respectively [3]. In addition, the number of stops of the trucks decreased by 9%–16%. Kari et al. developed an eco-friendly FSP algorithm and quantified the performance of the system using the simulation of urban mobility (SUMO) along with the comprehensive modal emission model [4]. A single isolated intersection was modeled with various truck fractions and total volumes, and the network-wide fuel savings were compared. From the results, the authors inferred that the proposed system could achieve 5% to 10% fuel saving. Zhao and Loannou proposed a signal priority control algorithm for trucks by using a co-simulation-based optimization control. They implemented the new algorithm in MATLAB and evaluated its performance using the VISSIM simulation software as a test bed [5]. Walraevens, Maertens, and Wittevrongel proposed a mathematical model for green extensions to freight vehicles on the main road. They analyzed average waiting times as a function of green extension durations on a macroscopic level via a stochastic analysis [6]. As a result of reviewing previous studies related to FSP, it was difficult to find a lot of relevant studies, and some of the previous studies mainly focused on developing and evaluating theoretical applications. It was hard to find an application that could be implemented in the field and estimate the impact.

The AERIS program was initiated by the United States Department of Transportation in 2011 [7,8]. It includes five transformative concepts: Eco-signal operations, eco-lanes, low emissions zones, eco-traveler information, and eco-integrated corridor management [9]. Each transformative concept contains a set of connected vehicle applications, which can improve the fuel efficiency and reduce the vehicle emissions. The eco-signal operations scenarios are defined as connected vehicle technologies implemented to decrease the fuel consumption and reduce greenhouse gas and criteria air pollutant emissions on arterials by reducing idling, stop-and-go behavior, and unnecessary accelerations and decelerations to improve the traffic flow at signalized intersections [9]. A recent study evaluated an eco-FSP using PARAMICS traffic simulation model [10]. An urban arterial in northern California, which has 27 signalized intersections, was modeled for the evaluation of various FSP scenarios. The simulation results showed that the eco-FSP realized a maximum of 4% fuel saving. This study is very valuable in that various FSP scenarios were implemented in the simulation software and evaluated from both a mobility perspective and an environmental perspective. However, as in the previous studies, this study also did not design the on-board unit (OBD) and roadside unit (RSU), which are needed to implement the FSP system in the actual field. The OBU generates signal requests and transmits them to the RSU. The RSU collects signal requests and sends them to the traffic controller via wireless communications.

The dynamic mobility application (DMA) program was initiated by the USDOT intelligent transportation systems joint program office in 2009 to advance the development, testing, commercialization, and deployment of transformative mobility applications. Thirty applications identified as having high-priority were grouped into seven categories within the DMA program [11]. The multi-modal intelligent transportation signal system (MMITSS) project, which is one of the seven categories, attempts to improve the transportation system mobility through signalized intersections and corridors using advanced communications to facilitate efficient travel of all modes, including passenger cars, pedestrians, bicyclists, transit vehicles, freight, and emergency vehicles, through the new-generation traffic signal control system. The MMITSS prototype development was conducted by the University of Arizona teamed with the University of California, Berkeley, Savari, Econolite, and an SAE J2735 communications standards expert to verify that the prototype was functioning correctly. Especially, the team focused on prototyping and testing practical infrastructure-oriented applications that lead to deployment rather than developing theoretical applications. The impacts of prototype applications were assessed by both collecting the field data from the MMITSS prototype and conducting simulation analyses to measure the performance. For the simulation analyses, the team developed two simulation systems in which the prototype algorithms are implemented: A software-in-the-loop simulation (SILS) system and a hardware-in-the-loop simulation (HILS) system. FSP is one of the MMITSS applications. The field data and simulation analyses demonstrated that MMITSS applications effectively improved the travel time and delay of the equipped vehicles. In particular, the FSP reduced the delay of connected trucks by maximum 20% compared to the base case [12]. However, the fuel consumption and air quality impacts of the FSP operation were not evaluated.

As heavy-duty freight vehicles consume a significant amount of fuel and produce significantly higher emissions compared to passenger cars, the potential impacts of FSP operation must be assessed from the environmental perspective. Therefore, the objective of this study is to evaluate the energy and environmental impacts of FSP under connected vehicle environment. In other words, the objective of this study is to demonstrate if the prototype system is also able to reduce the fuel consumption and emissions in the network level, although it was designed to enhance the mobility of trucks. For this study, the SILS system developed by the University of Arizona for the MMITSS project was utilized. The main difference between this study and previous studies is that the SILS system used in this study was designed to be implemented in the actual field.

The rest of the paper is organized as follows. In Section 2, the FSP priority control system, VISSIM network models, and simulation scenarios are explained. Section 3 presents the simulation results. Conclusions follow in Section 4.

## 2. Connected Vehicle Simulation Network Development

### 2.1. FSP Priority Control

This section describes the priority control model utilized for the study. The control logic developed in a study [13] was implemented. A mixed-integer linear program and a flexible implementation algorithm were utilized considering real-time vehicle actuation.

The priority control model includes the software components of the roadside unit (RSU) and the on-board unit (OBU) in the system, which uses IEEE 802.11p dedicated short-range communication (DSRC). When a truck enters a preset DSRC communication range, the OBU in the truck receives the signal phasing and timing (SPaT) and MAP data from each traffic signal controller. Thereafter, the OBU broadcasts an SRM through the priority request generator.

The RSU processes the SRM in the priority request server. The signal status message from the priority request server and priority arrangement from the traffic configuration manager is obtained by the signal priority algorithm module. The signal optimization problem is formulated and solved by the signal priority algorithm. A list of optimal signal control actions is generated by means of the critical points resulted from the optimal solution acquired by the flexible implementation algorithm. Lastly, the optimal plan is implemented by the traffic controller interface to provide a priority to the requested vehicle. If a priority request is newly added to the system, the new optimal plan is solved and implemented. When the priority request vehicle gets off the intersection or when the speed of the vehicle is out of a predefined threshold, the priority request is updated. This process is explained in detail in literature [13].

### 2.2. Simulation Model Framework

A software-in-the-loop simulation (SILS) system was utilized for this study. The system consists of four components running on two personal computers: The Econolite ASC/3 traffic controller emulator, the SRM distributor program, and the VISSIM microscopic traffic simulation software operated on a Windows system; and an RSU module operated on a Linux system. The system was synchronized at every simulation step using an Ethernet cable connection.

Once the VISSIM simulation model generates the location and speed data of individual connected vehicles, the SRM distributor program receives the simulated data. Further, the RSU receives the SRM data when the connected vehicle reaches its communication range. Given the operational conditions, the optimum signal-timing plan is estimated by the signal priority. The Econolite ASC/3 traffic controller interface receives the signal-timing plan and the VISSIM updates the signal plans.

### *2.3. VISSIM Network Model Development*

The study was conducted in a corridor of US Route 50-Chantilly, Virginia. The study arterial was also utilized as an MMITSS simulation testbed. The corridor is widely used as a main commuter route because it connects two highly congested highway interchanges on US Route 28 and I-66, and is used as an alternative to I-66. There are six signalized intersections within the study section, which extends over 2.4 km, as shown in Figure 1. The study section begins at the signalized intersection with Centreville Road and ends at the signalized intersections with Stringfellow Road. The typical section has three lanes for eastbound and westbound traffic. Some intersections have additional turning lanes for turning vehicles.

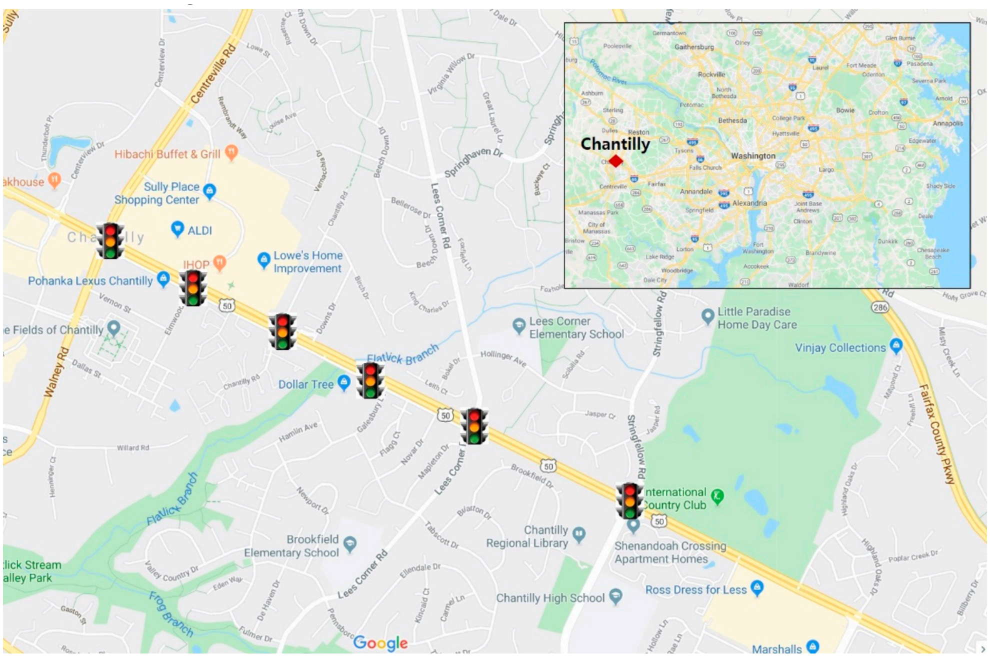



**Figure 1.** Study site (Source: Map data © 2019 Google).

The traffic flow rates measured in the morning peak period were between 2700 and 2800 veh/h in the eastbound and westbound directions. Severe congestion occurs along the corridor due to the closely spaced signalized intersections. In particular, there are significant traffic intrusions from the side streets at the intersections with Centreville Road and Stringfellow Road. The intersections are controlled by actuated signal coordination with optimized cycle lengths varying from 210–240 s. A large portion of the cycle time is assigned to the traffic movements on US 50.

The simulation input data, such as the traffic count and turning movement data, were provided by the Virginia Department of Transportation (VDOT). The volume-to-capacity ratio of the study corridor, which represents the traffic congestion levels, was 0.85 during the morning peak period.

A major freight route is simulated using the test corridor in this study. The FSP impacts under two congestion levels are presented in this section. The study examined the effects of 0.50 and 0.85 V/C ratios on 20% truck composition rates. While all the trucks were unequipped in the base-case scenarios, all the trucks were assumed equipped in the FSP scenarios. Besides, the trucks could only run between the east and west of the study corridor without turning. For the simulation of uncongested conditions, the origin–destination traffic demand data were proportionally adjusted to achieve the 0.50 V/C ratio.

The input parameters for the VISSIM model, which include speed distributions, saturation flow rates, and free-flow speeds, were calibrated against the traffic data provided by the VDOT. Field-measured flow rates were used to calibrate the car-following model by adjusting the three parameters for the Wiedmann 74 model such as the multiplicative parameter of the safety distance, the additive parameter of the safety distance, and the average standstill distance.

In addition, the real-world truck characteristics such as the weight distribution, power distribution, width, and length were adopted to accurately model the truck dynamics for the simulation. The study adjusted the default truck values in VISSIM to simulate a representative US truck fleet, as shown in Table 1. The power to weight ratio is a critical parameter to determine a truck's acceleration. Previous studies found that the vehicle acceleration is a very important variable to estimate the vehicle fuel consumption and emissions [14,15]. However, VISSIM cannot directly adjust the power to weight ratio of a vehicle type. Therefore, in this study, the power distribution and weight distribution were modified to obtain a realistic truck's acceleration behaviors based on a previous truck simulation study [16].

**Table 1.** Truck characteristics of VISSIM (Adapted from [16]).

| Classification. | Default VISSIM Truck Parameters | Modified VISSIM Truck Parameters |
|---|---|---|
| length (m) | 10.215 | 22.41 |
| width (m) | 2.496 | 2.6 |
| weight (kg) | 2800–40,000 | 9080–36,320 |
| power (kW) | 150–400 | 198–517 |

Totally four scenarios were developed, as shown in Table 2. For each scenario, the simulation model was iterated five times with a different random number seed. For the fleet composition, 20% of the origin-destination (O–D) traffic demand on the eastbound and westbound was allocated to trucks. In addition, 100% of the O–D traffic demand on the northbound and southbound was allocated to passenger cars. Consequently, the actual ratio of the trucks within the simulation is approximately 10% of all the vehicles.

**Table 2.** Simulation scenarios.

| Traffic Volume | Control Group | Experimental Group |
|---|---|---|
| | Base Case (MMITSS-Off Actuated Control) | Freight Signal Priority |
| under capacity (V/C ratio 0.5) | Scenario-1: 20% trucks and 80% passenger cars | Scenario-2: 20% connected trucks and 80% passenger cars |
| near capacity (V/C ratio 0.85) | Scenario-3: 20% trucks and 80% passenger cars | Scenario-4: 20% connected trucks and 80% passenger cars |

### *2.4. Emission Modeling*

The study utilized the MOVES model that was developed by the United States Environmental Protection Agency. We selected the MOVES model since it could estimate vehicle energy consumption and various emissions for both passenger vehicles and heavy-duty trucks using microscopic vehicle activity data. The microscopic analysis of the energy and emission estimation is important because the study computes instantaneous energy consumption and emissions using second-by-second vehicle speed and acceleration data as input variables. Most other studies use average speed as an input variable and thus cannot distinguish between facilities that operate at the same average speed. However, a vehicle consumes more fuel and produces higher emissions at high-speed arterial roadway sections than a constant speed highway section if both trips have identical average speeds. The proposed method can accurately estimate the energy consumption and emissions based on vehicle behavior changes in FSP operations. The study utilized the default MOVES variables without a specific calibration process since the study aimed to estimate the relative energy and environmental impacts of various FSP operations.

The MOVES database designated as "movesdb20121030" was used to retrieve the emission factors and calculate the fuel consumption and $CO_2$, HC, CO, $NO_X$. The vehicle type "passenger car" was selected to model the emissions exhausted by light-duty vehicles. There are five types of trucks in the MOVES model: Light commercial truck, single unit short-haul truck, single unit long-haul truck, combination short-haul truck, and combination long-haul truck. The vehicle type "single unit long-haul truck" is the closest vehicle modeled in the VISSIM model, and it was used to estimate the fuel consumption and emission rates for the truck in this study. For the computation of fuel consumption, energy consumption in kilojoules was first calculated and then converted to gasoline consumption using the density and lower heating value of gasoline using Equations (1) and (2) given below:

$$FC_{gram} = \frac{EC}{LHV_t} \tag{1}$$

$$FC_{gallon} = \frac{FC_{gram}}{D_t} \tag{2}$$

where $FC_{gram}$ is the fuel consumption in grams, $EC$ is the energy consumption in kJ, $LHV_t$ is the lower heating value of fuel type t, $FC_{gallon}$ is the fuel consumption in gallons, and $D_t$ is the density of fuel type t. Subsequently, the $CO_2$ emission was calculated using the oxidation fraction and carbon content of fuel, as shown below:

$$CO_{2atm} = EC \times OF_t \times CC_t \times \frac{44}{12} \tag{3}$$

where $CO_{2atm}$ is the atmospheric $CO_2$ in grams, $EC$ is the energy consumption in kJ, $OF_t$ is the oxidation fraction of fuel type t, and $CC_t$ is the carbon content of fuel type t.

For a quick computation of vehicle emissions, lookup tables were retrieved from the MOVES database by vehicle type and operating condition bins (designated OpModes). There are 23 OpModes in the MOVES model, and they are classified based on the vehicle specific power (VSP) and vehicle speed. Given the simulated speed profiles of the passenger cars and trucks from the VISSIM simulation runs, instantaneous OpMode was determined based on instantaneous vehicle speed and VSP calculated using the following equation:

$$VSP = \frac{Av + Bv^2 + Cv^3}{source\ mass} + va + 9.81\sin(a\tan(G))v \tag{4}$$

where $A$ is the rolling term, $B$ is the rotating term, $C$ is the drag term, $v$ is the vehicle speed in m/s, $a$ is the vehicle acceleration in m/s$^2$, and $G$ is the roadway grade in percentage. The coefficients in Equation (4) based on the vehicle type are available in the "SourceUseType" table. The energy consumption and emissions factors were then retrieved from the lookup tables by matching the OpModes.

## 3. Simulation Results

### 3.1. Comparison of Trucks

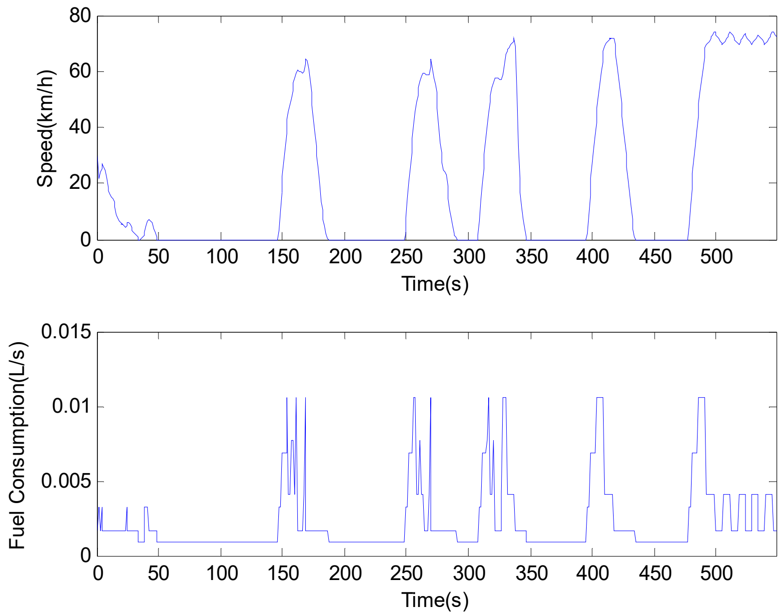
To assess the environmental impacts of FSP for connected trucks, the fuel consumption, $CO_2$, HC, CO, and $NO_X$ emission rates for normal trucks (NTs) and connected trucks (CTs) were compared, as shown in Table 3. The simulation results show that the FSP system in CTs significantly reduced the fuel consumption and vehicle emissions.

**Table 3.** Comparison of normal trucks and connected trucks.

| Classification | | Fuel (L/km) | $CO_2$ (kg/km) | HC (g/km) | CO (g/km) | $NO_X$ (g/km) |
|---|---|---|---|---|---|---|
| V/C = 0.5 | normal trucks | 0.28 | 655.27 | 0.11 | 1.76 | 0.70 |
| | connected trucks | 0.26 | 611.99 | 0.10 | 1.64 | 0.65 |
| | absolute difference | −0.02 | −43.29 | −0.01 | −0.13 | −0.05 |
| | relative difference | −6.6% | −6.6% | −7.3% | −7.2% | −6.5% |
| V/C = 0.85 | normal trucks | 0.39 | 908.59 | 0.17 | 2.24 | 0.95 |
| | connected trucks | 0.29 | 678.66 | 0.12 | 1.74 | 0.72 |
| | absolute difference | −0.10 | −229.94 | −0.05 | −0.50 | −0.23 |
| | relative difference | −25.3% | −25.3% | −28.7% | −22.2% | −24.3% |

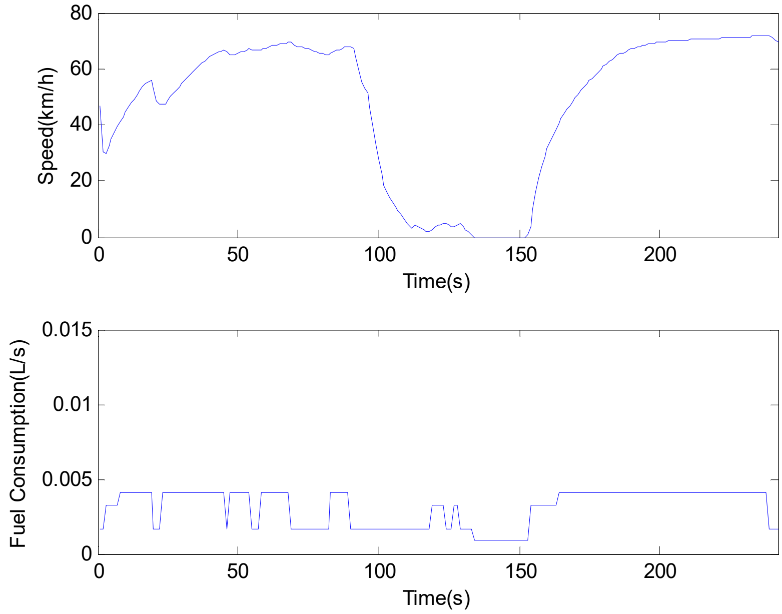
For the V/C ratio of 0.50, the FSP reduced the fuel consumption, $CO_2$, HC, CO, and NOx emissions in the connected trucks by 6.6%, 6.6%, 7.3%, 7.2%, and 6.5%, respectively. For the V/C ratio of 0.85, the FSP reduced the fuel consumption, $CO_2$, HC, CO, and NOx emissions in the connected trucks by 25.3%, 25.3%, 28.7%, 22.2%, and 24.3%, respectively. This demonstrates that an increased number of connected trucks in the network would benefit the environmental performance at the V/C ratio of 0.85.

To demonstrate the environmental impacts of the FSP system from an individual vehicle operating perspective, a speed profile of NTs was compared with one of the CTs, as shown in Figure 2. One speed profile was selected from all the NT trips, which represents the fuel consumption pattern of all the NTs. The average fuel consumption rate of all the NTs under the near capacity condition was computed and compared with the individual NTs' fuel consumption rates. The selected NT trip, which had the fuel consumption rate closest to the average of 0.4202 L/km, traveled 3.2 km for 548 s at an average speed of 21.1 km/h. A similar procedure was applied to select the representative speed profile of the CTs, which had the closest fuel consumption rate to the average of 0.2758 L/km, from all the CT trips under the near-capacity condition. The selected CT traveled 3.2 km for 242 s at an average speed of 47.4 km/h. As clearly seen in Figure 2, the subject NT stopped five times, whereas the CT stopped only once because the FSP system prioritized the trucks. Furthermore, the selected NT trip exhibited more aggressive driving patterns characterized by rapid acceleration and braking behaviors due to frequent stops.




**(a)**

**Figure 2.** *Cont.*




(**b**)

**Figure 2.** Trip comparison of normal truck (NT) and connected truck (CT). Note: (**a**) Sample trip of NT, Scenario-3; (**b**) sample trip of CT, Scenario-4.

## *3.2. Results of Passenger Cars*

This section presents the impacts of the FSP system on passenger cars. Table 4 demonstrates the fuel consumption and emissions of the passenger vehicles with and without FSP. The analysis includes both side-street passenger-car trips and the eastbound and westbound corridor passenger-car trips on the truck routes. Only the northbound and southbound trips from the side streets were considered in the side-street passenger-car trips in order to eliminate the impact of turning movements.

**Table 4.** Impact of the freight signal priority (FSP) on passenger cars.

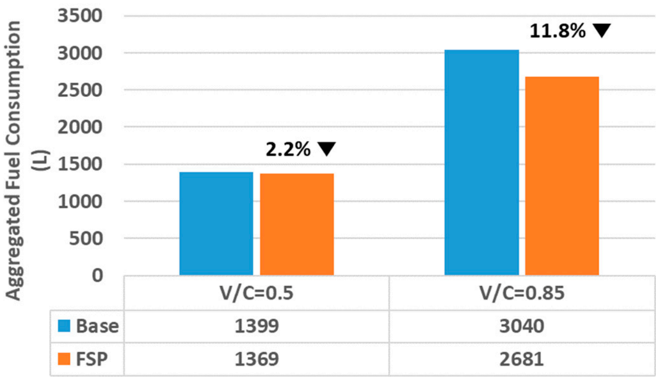
| Classification | | | Fuel (L/km) | $CO_2$ (kg/km) | HC (g/km) | CO (g/km) | $NO_X$ (g/km) |
|---|---|---|---|---|---|---|---|
| Passenger Cars on Side Streets | V/C = 0.5 | actuated control | 0.082 | 193.0 | 0.008 | 0.870 | 0.026 |
| | | freight signal priority | 0.095 | 222.9 | 0.008 | 0.861 | 0.026 |
| | | relative difference | 15.5% | 15.5% | 2.7% | −1.0% | 1.0% |
| | V/C = 0.85 | actuated control | 0.130 | 305.2 | 0.010 | 0.941 | 0.030 |
| | | freight signal priority | 0.263 | 620.1 | 0.013 | 0.977 | 0.033 |
| | | relative difference | 103.2% | 103.2% | 27.8% | 3.8% | 11.2% |
| Eastbound and Westbound Passenger Cars | V/C = 0.5 | actuated control | 0.068 | 159.1 | 0.008 | 0.853 | 0.025 |
| | | freight signal priority | 0.064 | 150.6 | 0.007 | 0.760 | 0.023 |
| | | relative difference | −5.3% | −5.3% | −10.2% | −10.9% | −10.1% |
| | V/C = 0.85 | actuated control | 0.089 | 208.6 | 0.009 | 0.872 | 0.027 |
| | | freight signal priority | 0.068 | 159.0 | 0.007 | 0.726 | 0.022 |
| | | relative difference | −23.8% | −23.8% | −19.4% | −16.7% | −17.6% |

The simulation results indicate that the FSP effectively reduced the fuel consumption and emissions in the passenger vehicles along the truck route through traffic signal-controlled intersections compared to the base case scenarios. In particular, the FSP reduced the fuel consumption and $CO_2$ emission by maximum 23.8% and HC, CO, and NOx emissions by maximum 19.4%, 16.7%, and 17.6%, respectively, in the passenger cars along the truck route. The results prove that FSP effectively facilitates positive environmental impacts by passenger vehicles that traverse on the truck route.

However, the study also found some negative impacts of the FSP implementation in the form of increased fuel consumption and emissions on the side streets. Specifically, the implementation increased the fuel consumption and $CO_2$ emissions by a maximum of 103.2% and the HC, CO, and NOx emissions by maximum 27.8%, 3.8%, 11.2%, respectively, in the passenger cars on the side streets. The priority system facilitates an extended green signal time for the remaining phases, which typically reduces the green signal time to the side streets. In this study, these reduced green signal times to the side street increased the delays of the side streets and the fuel consumption and emissions of the side-street vehicles.

### 3.3. System-Wide Impacts and Different Truck Impacts

The study also quantified the system-wide environmental impacts of freight vehicles and passenger cars with and without FSP, as shown in Figure 3; the total fuel consumed and the $CO_2$, HC, CO, and $NO_X$ emitted by all the passenger cars and trucks are aggregated and compared for the individual scenarios. Simulation results demonstrate that the FSP reduced the fuel consumption in both freight and passenger vehicles. Specifically, the implementation of FSP reduced the network-wide energy consumption by 2.2% and 11.8% for the V/C ratios of 0.5 and 0.85, respectively. It was also observed that the FSP reduced the $CO_2$, HC, CO, and $NO_X$ emission by maximum 11.8%, 28.3%, 24.8%, and 25.9%, respectively, for a V/C ratio of 0.85. The results demonstrate that most energy savings and emission reductions were observed for the V/C ratio of 0.85, and under these limited simulation scenarios and network conditions, the FSP operation effectively increased the environmental benefits by truck and passenger cars in the network.

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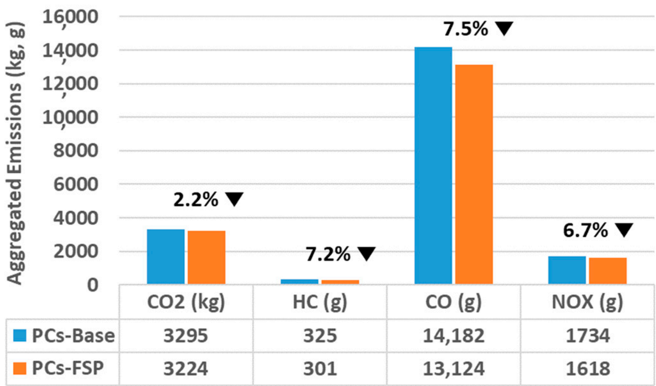
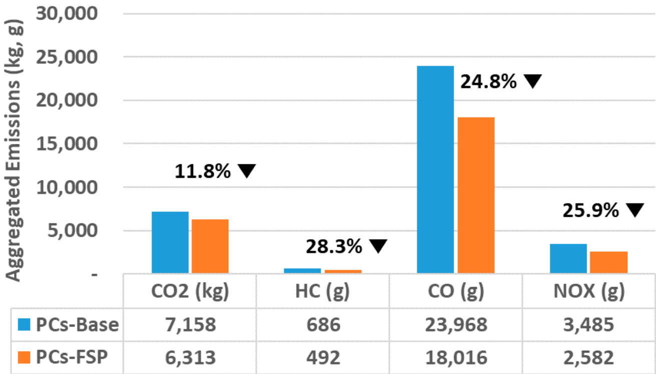



(**b**)

**Figure 3.** *Cont.*




(**c**)

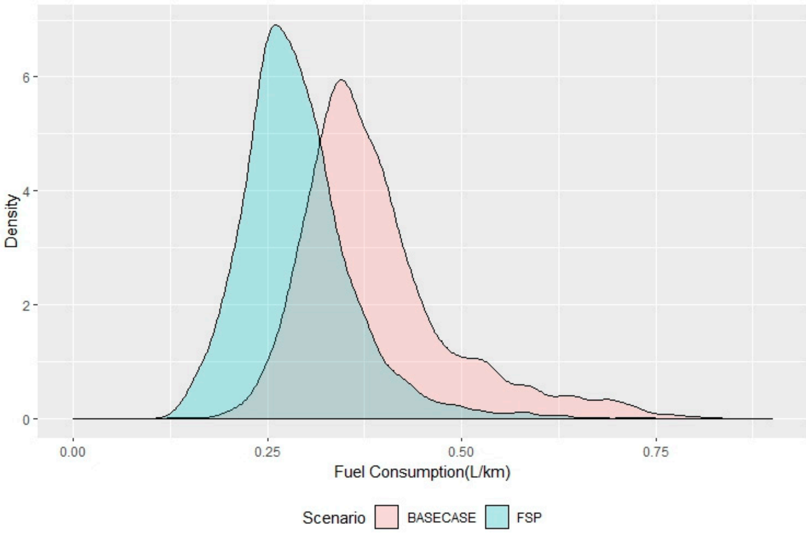
**Figure 3.** System-wide impacts of FSP on fuel consumption and emissions. Note: (**a**) Aggregated fuel consumption comparison; (**b**) comparison of emissions at V/C = 0.5; (**c**) comparison of emissions at V/C = 0.85.

The study also investigates the environmental impacts of the FSP for different truck types. Three additional truck models were used to estimate the fuel consumption and vehicle emissions. Specifically, the base case and the FSP scenario under the near-capacity condition were tested to quantify the impacts of different truck types. Table 5 demonstrates that the difference in the truck type does not significantly affect the environmental impacts of the FSP. In particular, combination trucks reduced more fuel consumption and emissions than single unit-haul trucks, except the HC emission. However, the results indicate that the impacts of different trucks are relatively small under the specific simulation scenario and network condition.

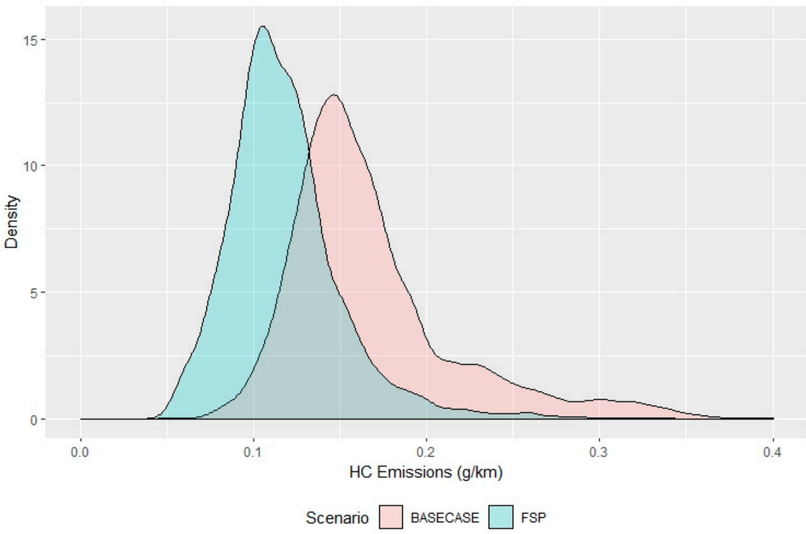
**Table 5.** System-wide impact of different trucks under a volume/capacity (V/C) ratio of 0.85.

| Classification | | Fuel (L) | $CO_2$ (kg) | HC (kg) | CO (kg) | $NO_X$ (kg) |
|---|---|---|---|---|---|---|
| single unit long haul truck | actuated control | 3040 | 7158.237 | 0.686 | 23.968 | 3.485 |
| | freight signal priority | 2681 | 6313.157 | 0.492 | 18.016 | 2.582 |
| | relative difference | −11.8% | −11.8% | −28.3% | −24.8% | −25.9% |
| single unit short haul truck | actuated control | 3147 | 7409.620 | 0.733 | 25.106 | 3.758 |
| | freight signal priority | 2773 | 6528.901 | 0.527 | 19.095 | 2.801 |
| | relative difference | −11.9% | −11.9% | −28.1% | −23.9% | −25.5% |
| combination long haul truck | actuated control | 4605 | 10,844.098 | 0.413 | 17.864 | 4.382 |
| | freight signal priority | 3973 | 9356.323 | 0.303 | 13.384 | 3.356 |
| | relative difference | −13.7% | −13.7% | −26.6% | −25.1% | −23.4% |
| combination short haul truck | actuated control | 4505 | 10,608.296 | 0.413 | 17.862 | 4.293 |
| | freight signal priority | 3885 | 9148.055 | 0.303 | 13.384 | 3.272 |
| | relative difference | −13.8% | −13.8% | −26.6% | −25.1% | −23.8% |

During the study, a number of statistical analyses were conducted to identify if two fuel consumption and emission results with and without FSP are significantly different from each other. Student's $t$-tests were performed assuming the null hypothesis such that the means of two populations are equal. The $t$-test results demonstrated that all the $p$-values were less than 0.0001, indicating that the fuel consumption and emissions were significantly reduced with the implementation of FSP. For the illustration, the distribution of the fuel consumption and HC emission rates are shown in Figure 4. The figure clearly demonstrates that the fuel consumption and HC emission rates of the connected trucks are differently distributed when compared to the results of normal trucks.




(**a**)

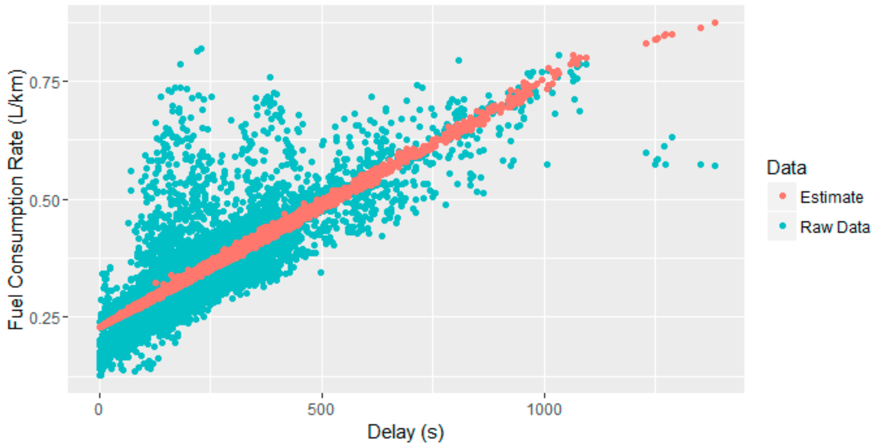



(**b**)

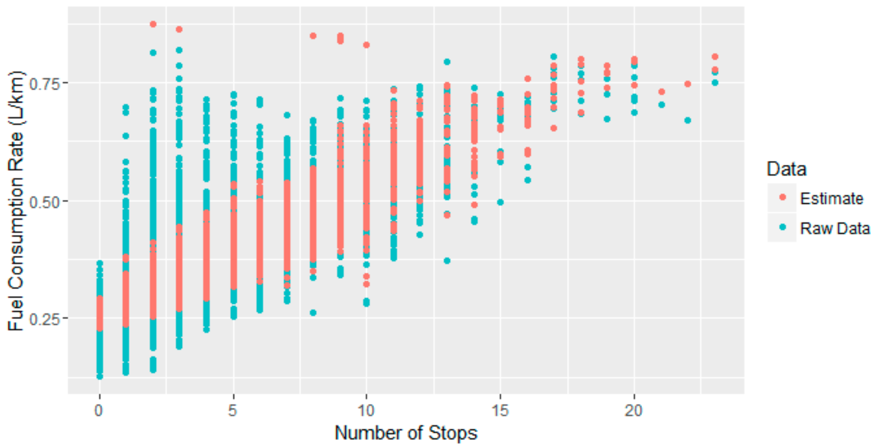
**Figure 4.** Distributions of fuel consumption and hydrocarbon (HC) emission rates. Note: (**a**) Fuel consumption; (**b**) HC emissions.

A multiple linear regression was conducted to investigate the relationship of fuel consumption with two independent variables: Delay and number of stops. The fuel consumption rates were regressed with the delay and number of stops for both normal and connected trucks in the given framework shown in Equation (5). The R-square was obtained as 0.6459, indicating that errors exist in the estimation as shown in Figure 5; whereas, all the coefficients were significant, as shown in Table 6. The regression result demonstrates that between the two factors, the number of stops has more influence on the fuel consumption because the estimate of number of stop is much greater than the estimate of delay.

$$fuel\ consumption\ rate = \alpha + \beta \times Delay + \chi \times Stop \quad (5)$$




(**a**)




(**b**)

**Figure 5.** Scatter plot of fuel consumption rates and estimated fuel consumption rates Note: (**a**) Delay versus fuel consumption rate; (**b**) number of stops versus fuel consumption rate.

**Table 6.** Multiple linear regression result.

| Classification | Estimate | Standard Error | *t*-Value | Pr(> \|t\|) |
|---|---|---|---|---|
| Intercept | 0.2286 | 0.00121 | 188.853 | $<2 \cdot 10^{-16}$ |
| Delay | 0.000461 | 0.000009352 | 49.295 | $<2 \cdot 10^{-16}$ |
| Stop | 0.003672 | 0.000554 | 6.628 | $3.6 \cdot 10^{-11}$ |

## 4. Discussion

Connected and automated vehicles (CAVs) are an influential emerging technology expected to generate transformative improvements in the transportation system. Specifically, CAVs can extend the benefits of the intelligent transportation system (ITS) through the real-time exchange of information between vehicles and infrastructure. CAV technology encompasses a set of applications to connect vehicles to each other and to the road infrastructure using vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, collectively known as V2X. These technologies generate real-time data that can assist drivers in avoiding congestion, reducing vehicle stops, and achieving optimal fuel efficiency. The real-time data exchange provided by CAV applications offers many opportunities for proactive network-wide traffic management and thus has the potential to overcome the current limitations of traditional data collection approaches.

FSP is one of CAV applications to improve the mobility of trucks. As explained in the Introduction Section, most previous FSP studies focused on the evaluation of the travel delay and the number of stops.

The significance of this study is that this study first attempts to evaluate the environmental impacts of a connected FSP system using a real-world CV application. Recently, various CAV applications have been developed, tested, and implemented on new roadway facilities worldwide. However, the energy and environmental impacts were frequently ignored for the new roadway facilities. The study found that the implementation of FSP saved the network-wide fuel consumption by up to 11.8 % and reduced the $CO_2$, HC, CO, and $NO_X$ emission by a maximum of 11.8%, 28.3%, 24.8%, and 25.9%, respectively, for the specific study corridor. However, the study also found that the FSP operation significantly increased fuel consumption by up to 103% and emissions up to 27.8% for the vehicles on the side streets. The results indicate the problem of the current FSP system which provides extended green time for the vehicles on the major streets and reduces the green time of the vehicles on the side-streets. Even if the FSP system improves system-wide mobility and energy efficiency, we may need a new system that can reduce the disadvantages of the side-street vehicles. One of possible options is a decentralized cycle-free traffic signal system that can be utilized under the CAV environment. Decentralized traffic control systems require the relevant traffic information from the surrounding roadway facilities using CAV technologies and can utilize cycle-free traffic signal controllers. The cycle-free traffic control system can improve the mobility and energy efficiency for both major and side-street vehicles since it does not require green-extension from major streets for an FSP system.

Given that CAV technologies continuously improve transportation mobility and safety, they also provide an opportunity to reduce transportation energy consumption and emissions. New CAV applications should consider the energy and environmental impacts of the new transportation system.

## 5. Conclusions

This study evaluated the energy and environmental impacts of FSP under connected vehicle environment by utilizing a connected vehicle simulation testbed developed for an MMITSS simulation. The simulation platform consists of the VISSIM microscopic traffic simulation software, the SRM distributor program, an RSE module, and the econolite ASC/3 traffic controller emulator. The MOVES model was used to estimate the vehicle fuel consumption and emissions.

From the simulation study, it was found that the implementation of FSP significantly reduces the fuel consumption and emissions for both connected trucks and general passenger cars. It was observed that the implementation of FSP reduced the fuel consumption of trucks and passenger vehicles on the test corridor by maximum 25.3% and 23.8%, respectively, and the $CO_2$, HC, CO, and NOx emissions by 25.3%, 25.3%, 28.7%, 22.2%, and 24.3% for the connected trucks and by 23.8%, 19.4%, 16.7%, and 17.6% for the passenger cars, respectively. However, FSP increases the fuel consumption and emissions for the side-street vehicles due to the reduced green signal times on the side streets. The fuel consumption and greenhouse gas emissions of side-street vehicles increased by maximum 103.2% due to severe congestions after the implementation of the FSP. While the FSP significantly increases the fuel consumption and emissions on the side streets, the system-wide benefits of the network increase substantially, especially in the high truck composition scenario. The simulation study demonstrates that the FSP constantly reduces the fuel consumption and emissions of trucks and passenger cars relative to the base-case scenarios. It is to be noted that the FSP operation effectively increases the environmental benefits when the system is operated under the near-capacity condition compared to the uncongested condition.

Further study should quantify the impacts of the FSP application from the safety perspective because it is normally known that the FSP application can decrease hard stops and red-light runs causing severe accidents. The SILS system utilized in the study along with the safety surrogate assessment model can function as a tool for the analysis of safety impacts. In addition, further research is recommended to develop a new FSP application that reduces system-wide delays, fuel consumption, and emissions considering both truck routes and side-street vehicles. As the CAV technology can collect the network-wide traffic data, a further study will develop new FSP applications that optimize the network-wide impacts.

**Author Contributions:** S.P. designed the study, analyzed the data, and wrote the manuscript; K.A. designed, conducted the study, and reviewed and reformatted the overall paper; H.A.R. provided suggestions to improve the study and the manuscript.

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