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Develop and Deploy a Safe Truck Platoon Testing Protocol for the Purdue ARPA-E Project in Indiana

Greg Shaver, Miles Droege

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16. Abstract
Hilly terrain poses challenges to truck platoons using fixed set speed cruise control. Driving the front truck efficiently on hilly terrain improves both trucks fuel economies and improves gap maintenance between the trucks. An experimentally-validated simulation model was used to show fuel savings for the platoon of 12.3% when the front truck uses long horizon predictive cruise control (LH-PCC), 8.7% when the front truck uses flexible set speed cruise control, and only 1.2% when the front truck uses fixed set speed cruise control. Purdue, Peloton, and Cummins have jointly configured two Peterbilt 579 trucks for relevant combinations of: (1) coordinated shifting, (2) constant or variable platoon gap controls, (3) flexible or constant speed setpoint cruise control of the front trucks, and (4) long-horizon predictive cruise control (LHPCC) of the front truck. Confirmation of this functionality during platooning was demonstrated at the Continental Test track in Uvalde, Texas. In Indiana, on-road experiments were limited to single truck operation with long-horizon predictive cruise control, flexible set speed cruise control, and constant setpoint cruise control. Data from all of the above was used to improve the fidelity of simulations used to arrive at the fuel savings and gap control findings for hilly terrain per what is summarized in the findings section. Additionally, in early summer 2020, Purdue submitted to, and received approval from, INDOT for a safe truck platoon testing protocol (located in this report's appendix), which could not be implemented in Indiana before the end of the project because of COVID-19. Presentations of the subject matter at COMVEC, MAASTO, Purdue Road School, and the Work Truck Show are listed in the appendix.

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class 8 trucking, fuel efficiency, highway transportation, freight transportation, safety improvement systems, truck platooning, safety, efficiency

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EXECUTIVE SUMMARY

Introduction

With ever growing concerns about rising CO2 levels in the atmosphere and an increasing interest in reducing the cost of operating a commercial vehicle fleet, there is great incentive for both the government and the heavy-duty vehicle industry to reduce the fuel consumption of commercial vehicles. Two-truck platooning promising to improve the safety and fuel efficiency of freight transportation. New control strategies are required for platooning on roads with hilly terrain. A significant portion of US highways have grade greater than 2% (22% of 55 mph and 13% of 75 mph US highways have grade greater than $\pm 2\%$). This work focused on filling the research gap by comparing different control strategies to improve platooning on a route with hilly terrain, specifically road grade up to $\pm 4.5\%$.

Findings

Hilly terrain poses challenges to truck platoons using fixed set speed cruise control. Driving the front truck efficiently on hilly terrain improves both trucks fuel economies and improves gap maintenance between the trucks. An experimentally-validated simulation model was used to show fuel savings for the platoon of 12.3% when the front truck uses long horizon predictive cruise control (LHPCC), 8.7% when the front truck uses flexible set speed cruise control, and only 1.2% when the front truck uses fixed set speed cruise control.

Implementation

Purdue, Peloton, and Cummins have jointly configured two Peterbilt 579 trucks for relevant combinations of (1) coordinated shifting, (2) constant or variable platoon gap controls, (3) flexible or constant speed setpoint cruise control of the front trucks, and (4) long-horizon predictive cruise control (LHPCC) of the front truck. Confirmation of this functionality during platooning was demonstrated at the Continental Test track in Uvalde, Texas. In Indiana, on-road experiments were limited to single-truck operations with long-horizon predictive cruise control, flexible set speed cruise control, and constant setpoint cruise control. Data from all of the above was used to improve the fidelity of simulations used to arrive at the fuel savings and gap control findings for hilly terrain per what is summarized above in the findings section. In addition, in the early summer of 2020, Purdue submitted to and received approval from INDOT for a safe truck platoon testing protocol (located in this report's appendix), which could not be implemented in Indiana before the end of the project because of COVID-19.

CONTENTS

TABLE LIST

FIGURE LIST

1. INTRODUCTION

With ever growing concerns about rising CO2 levels in the atmosphere and an increasing interest in reducing the cost of operating a commercial vehicle fleet, there is great incentive for both the government as well as the heavy-duty vehicle industry to reduce the fuel consumption of commercial vehicles. Both the population and the per capita income of the world are continuing to grow. With this growth comes a rise in the demand for goods and services, and thus an increase in need for commercial transportation. Commercial vehicles not only comprise a large portion of the current global transportation sector's energy demand, but in the Exxon Mobile 2019 *Outlook for Energy: A Perspective to 2040*, the increase of the heavy-duty sector is predicted to account for over 50% of the growth in energy demand from 2017 to 2040 (EPA, 2021).

The heavy-duty transportation sector is not only a major part of the economy globally, but also in the United States. The entire transportation sector accounts for 28% of the greenhouse gas emissions in the United States and is the sector with the highest greenhouse gas emissions in the nation. Within the transportation sector, heavy-duty and medium-duty vehicles account for the second highest emissions after light-duty vehicles (ExxonMobil, 2019). However, while light-duty vehicles trend toward hybridization and electrification, heavy-duty trucks struggle to make the transition due to the long periods of time that they operate and the low energy density that currently plagues battery technology.

There is not just an interest in reducing fuel consumption to reduce the greenhouse gas emissions of heavy-duty vehicles, but also to reduce fuel costs. A breakdown in the cost of a class 8 truck in the United States reveals that fuel is the second largest expense, after driver wages, at 24% of the cost per mile (Endres, n.d.). Small improvements in fuel economy of a class 8 vehicle can yield large monetary savings for operating costs of a fleet of class 8 trucks, and therefore lead to fleet operating companies improving their profit margins.

Platooning has been shown to improve fuel economy for all vehicles in the platoon. Heavy duty platoons have been shown to improve fuel economy for closed course tests (Lammert et al., 2014; McAuliffe, et al., 2018; Tsugawa, 2014), limited traffic on-road tests (Lu & Shladover, 2011; Tsugawa et al., 2011), and nominal traffic on-road tests (Alam et al., 2015). But the road grades for these tests were either not discussed or were small (less than $\pm 2\%$) for all of the results except those presented by Alam et al. (2015).

In order to platoon efficiently on US highways, new control strategies must be developed for platooning on roads with hilly terrain. Alam et al. (2015) showed that a platoon becomes more difficult to control on a route with steep grade. These experimental results showed increased braking and fuel consumption for a platoon using a cooperative adaptive cruise control on the front truck for a route with hilly terrain, greater than $\pm 2\%$. Additionally, a significant portion of US highways have grade greater than 2%. Wood et al. (2016) shows that 22% of 55 mph and 13% of 75 mph US highways have grade greater than $\pm 2\%$. While Alam et al. (2015) provides one method to improve platoon fuel economy on steep grade, but the work mentions that "more advanced control techniques are required to effectively platoon over such terrain." Therefore, this work will focus on filling the research gap by comparing different control strategies to improve platooning on a route with hilly terrain, specifically road grade up to $\pm 4.5\%$.

2. SIMULATION FRAMEWORK

A high-fidelity simulation framework was developed to simulate single truck and two truck platoon operation on real world test routes. At the basis of the simulation framework lies a high-fidelity black-box vehicle model provided by Cummins Inc. and a high-fidelity black-box platoon gap controller provided by Peloton Technologies.

In a single truck simulation configuration, the simulation consists of one vehicle model, a speed tracker, a speed profile, and road grade data for the route as seen in Figure 2.1. In a two-truck platoon simulation configuration, the simulation consists of two vehicle models, a speed tracker, a speed profile, a follow truck platoon gap controller, and road grade data for the route as seen in Figure 2.2. The lead vehicle model is controlled by a PI speed tracker and the follow truck model is controlled by the platoon gap controller. The speed profile is one of the main focuses of this research effort. Speed profiles collected from different types of lead truck speed controllers are analyzed, developed, and tested throughout the rest of this work. Speed profiles for different driver models are experimentally collected using the single truck experimental setup. Then, the experimental speed profiles are fed into the simulation framework where a PI controller tracks the speed profile. In both single truck and two-truck platoon configurations road grade data was collected for each route prior to the simulation using the on-board GPS.

The Cummins provided class 8 vehicle model used for the front and follow trucks iterates with respect to time and takes inputs including vehicle weight, vehicle drag coefficient, rolling resistance coefficient, road grade, commanded torque, commanded foundation brake, and commanded gear. The vehicle model provides outputs including vehicle speed, engine speed, engine torque, fuel consumption, and foundation brake fraction. The gear input is initially set up such that gear is automatically selected in the black-box vehicle model based on shifting maps. Later on in this effort, a shifting strategy will be discussed in which the gear is manually selected. The vehicle drag coefficients seen in Table 2.1 were experimentally

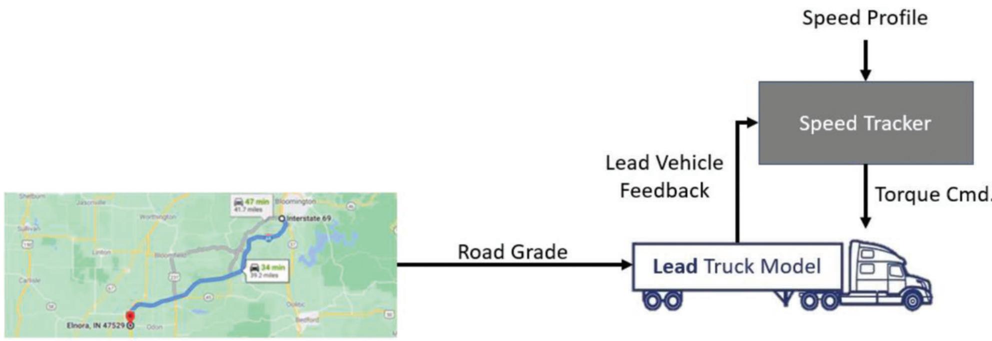

Figure 2.1 Single truck simulation framework.

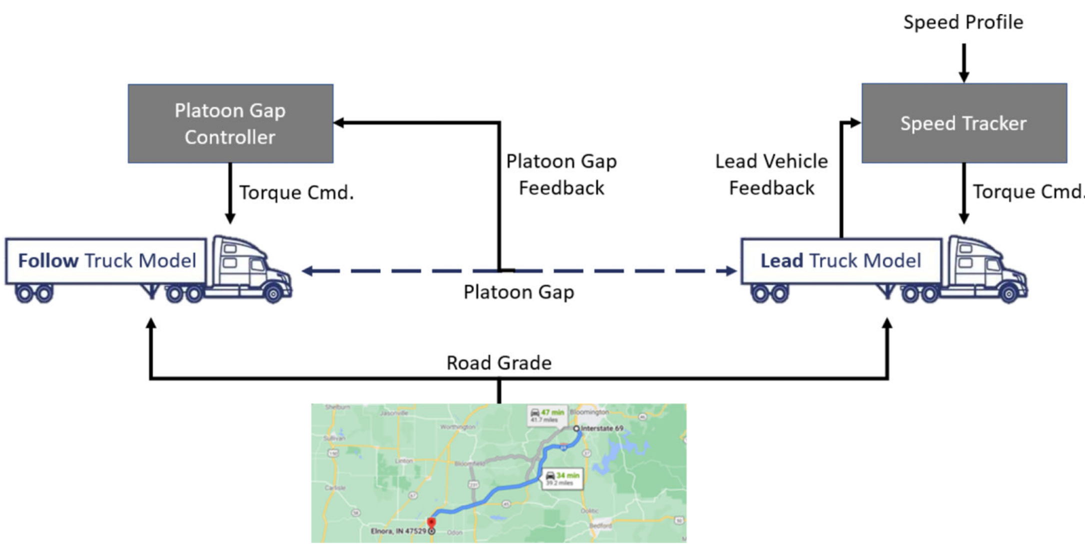

Figure 2.2 Two-truck platoon simulation framework.

TABLE 2.1
Experimentally Derived Drag Coefficients

	Drag Coefficient
Single Truck	0.58
Lead Truck in Platoon	0.55
Follow Truck in Platoon	0.49

calculated at a truck separation of 16.7 m using the method described in Foster. This is a valid approximation as the trucks are operated at a desired platoon gap distance of 16.7 m for a majority of the time and the drag coefficients for the lead and follow truck are nearly constant for a platoon gap of 16.7 m to 30 m (Salari, 2016). Although the simulated platoon gap grows to a maximum of nearly 50 m at times in the simulations reported in this paper, these are isolated events and occur for a short amount of time. Therefore, it is reasonable to assume that the experimentally derived drag coefficient can be approximated as constants for this simulation framework.

The Peloton provided platoon gap controller acts as a pseudo driver model for the rear truck. It takes inputs including both trucks' engine torques, vehicle speeds, current truck gear ratios, the desired platoon gap, and the measured platoon gap. While the desired platoon gap can be changed, it is kept at 16.7 m for this paper, to maximize aerodynamic benefits while maintaining a safe following distance. The platoon gap controller actively tries to maintain the desired platoon gap, and it commands engine torque and foundation brake commands to the follow truck vehicle model to maintain this gap.

3. SINGLE TRUCK EXPERIMENTAL SET-UP

A Peterbilt 579 Model Year 2019 sleeper cab was available for experimental testing. It is powered by a Cummins X15 Efficiency Series engine mated to an Eaton Endurant 12 speed automated manual transmission. The truck is connected to 53′ Wabash National DuraPlate dry van trailers with trailer skirts and is loaded down with concrete blocks so that the total tractor-trailer GVW is 65,000 lbs.

The truck is equipped with Peloton's PlatoonPro system, which is integrated into the vehicle's controller area network (CAN). This allows the PlatoonPro system to read data from the vehicle, engine, transmission, and brake module. It also allows for various parameters, such as engine torque, to be commanded during a platoon. Vehicle data obtained from the experimental testing comes from Peloton's engine control unit (PECU), which has an internal GPS that allows it to log vehicle parameters as a function of time and location.

Speedgoat real-time target machines were installed to enable the implementation of custom Simulink algorithms. The Speedgoat machines are equipped with separate GPS units, and they are able to communicate both over CAN and through separate connections to the engine and PECU. This gives them the ability to command engine torque, retarder torque, transmission gear number, and cruise control setpoint. A Cummins provided Simulink functionality allowed for a custom velocity profile to be commanded as a function of GPS location. This functionality will be utilized in the implementation of a generated optimal speed profile discussed later on in this paper.

The route used for analysis in this effort is US Interstate highway 69 between Bloomington and Elnora, Indiana seen in Figure 3.1. This is nearly 40-miles one-way with road grade up to $\pm 4.5\%$. The root mean square road grade is 1.78%. A plot of the route grade can be seen in Figure 3.2 and a histogram of the grade can be seen in Figure 3.3.

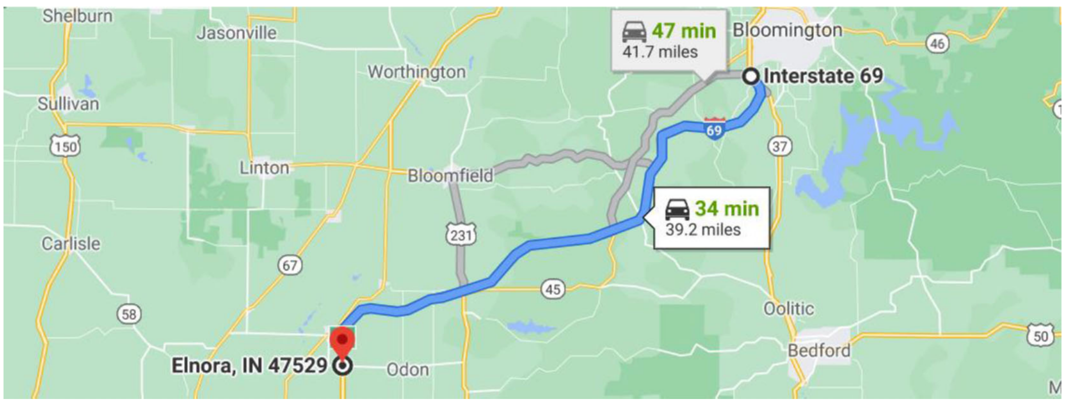

Figure 3.1 Hilly terrain test route (I-69).

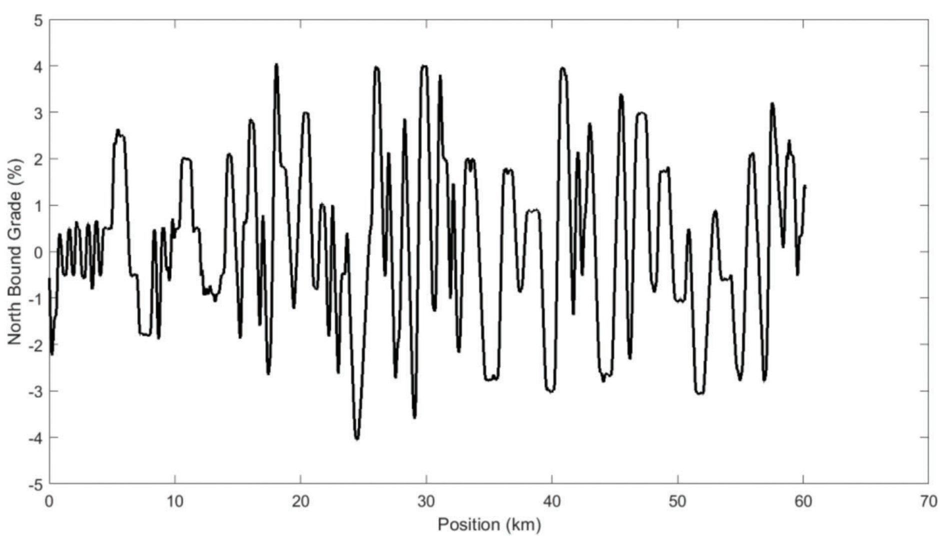

Figure 3.2 Hilly terrain test route (I-69) road grade.

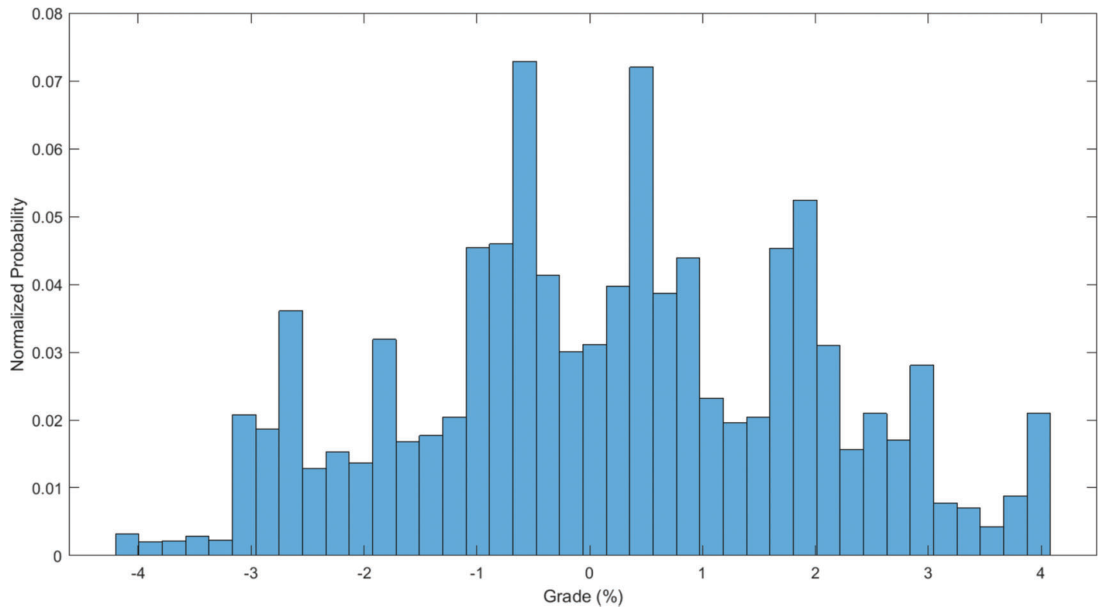

Figure 3.3 Hilly terrain test route (I-69) road grade distribution.

4. SIMULATION VALIDATION

The high-fidelity simulation framework is validated using two-truck platoon experimental data. A two-truck platoon was operated on Continental's Uvalde Proving Grounds in Uvalde, Texas. This closed course is nearly 8.5 miles and has grade up to $\pm 2\%$. Lead and follow vehicle data was collected from a test in which the front truck used a flexible set speed cruise controller. The front truck's speed and grade data was used as inputs to the simulation framework.

Comparing the simulation and experimental data shows that the simulation reasonably captures the dynamics of experimental platoon testing. Figure 4.1 shows the experimental data plotted against the simulation data for one lap. The simulated lead truck tracks the experimental velocity within ± 0.5 mph. The simulated lead engine torque tracks the experimental torque within ± 300 ft-lb in most cases and within ± 500 ft-lb at the extremes. The simulated follow truck tracks the experimental velocity within ± 1.5 mph. The simulated follow engine torque tracks the experimental torque

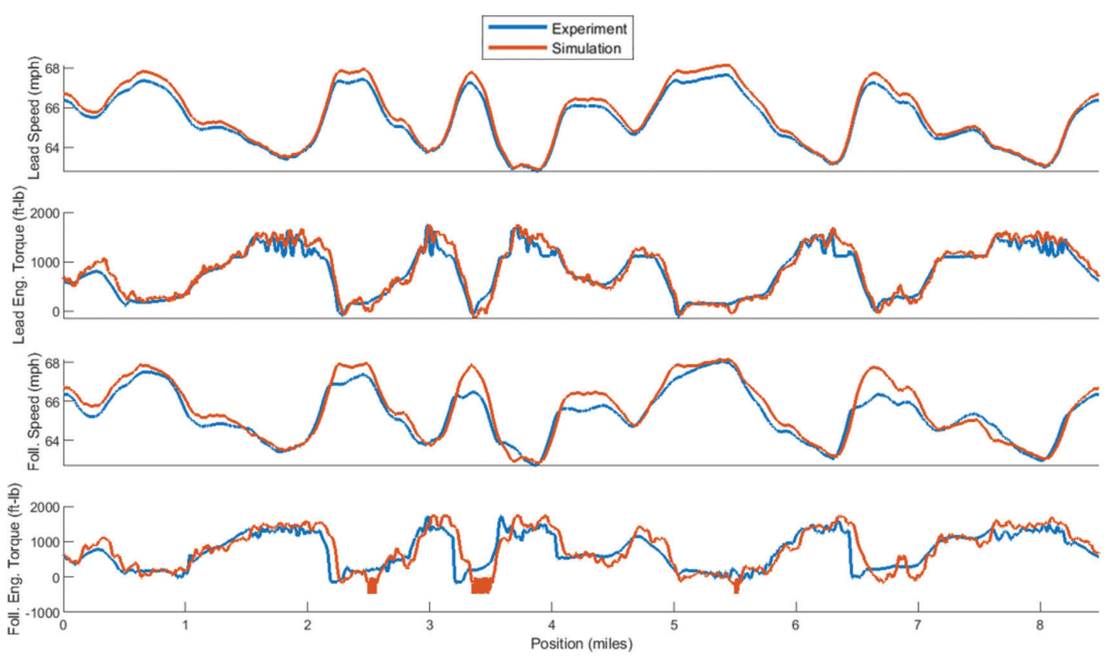

Figure 4.1 Platoon simulation validation.

TABLE 4.1
Closed-Track Cumulative Engine Statistics

		Experiment	Simulation
Single Truck	Pos. Work (MJ)	60.438	65.645
	Neg. Work (MJ)	-00.206	-00.045
Platoon-Lead Truck	Pos. Work (MJ)	58.901	63.585
	Neg. Work (MJ)	-00.148	-00.095
Platoon-Follow Truck	Pos. Work (MJ)	54.823	60.174
	Neg. Work (MJ)	-00.457	-00.943

within ± 500 ft-lb in most cases and within $\pm 1{,}500$ at the extremes.

While the instantaneous engine torque error may be high for both trucks, the simulation cycle positive and negative engine work show a much higher correlation with the experimental results (Table 4.1). Specifically, the positive work savings compared to a single truck show a high correlation between the simulation and experimental results. The positive work savings for the lead truck compared to the single truck is 2.5% using the experimental data and 3.1% using the simulation data. The positive work savings for the follow truck compared to the single truck is 9.3% using the experimental data and 8.3% using the simulation data. The negative work savings show less correlation, but this can partly be attributed to the fact that the track grade is relatively low and therefore neither the experimental truck or simulated truck use much engine retarder in the first place. The fact remains though, that the general trends in experimental vehicle speed and engine power are accurately captured in the simulation.

5. FIXED AND FLEXIBLE SET SPEED CRUISE CONTROL

Cruise control is a commercially available technology on Class 8 Heavy-Duty vehicles. In this effort, two types of commercially available cruise control are tested and analyzed over the I-69 route. The first is a fixed set speed cruise control in which a speed is set by the driver and the cruise control actively tries to maintain that set speed. The second is a flexible set speed cruise control in which a speed is set by the driver, but the vehicle's speed is allowed to deviate between a lower and upper limit from the set speed to improve fuel economy. The flexible set speed's configuration used in this work has a lower limit of -6 mph and an upper limit of 3 mph. For example, if the set speed is 62 mph, the vehicle's speed is allowed to deviate between 56 and 65 mph. In this configuration, the vehicle typically slows down on uphill section and speeds up on downhill sections. These speed deviations allow the vehicle to operate more efficiently while maintaining nearly the same trip time between the route start and end points.

A single Peterbilt 579 truck using fixed and flexible set speed cruise controllers was operated on the north and south bound I-69 route in order to capture experimental velocity profiles. The experimental fixed and flexible set speed velocity profiles were then used as inputs to the simulation frameworks. Using these simulations, an apt comparison can be made between the effect of using fixed and flexible set speed cruise controllers on two-truck platoons.

The north and south bound I-69 single truck simulation results demonstrate that a truck using flexible set speed cruise control consumes less fuel and uses less engine retarder than a truck using fixed set speed cruise control. The flexible set speed controller reduced single truck fuel consumption by 5.7% to 8.0%, and it reduced retarder work by 70.4% to 76.4% compared to a single truck using the fixed set speed controller (Table 5.1). The improvements came at no cost to the trip time. In fact, the single truck simulation using the flexible set speed was about 1% faster than the simulation using the fixed set speed.

The two-truck simulation results also demonstrate that a platoon using flexible set speed cruise control on the front truck consumes less fuel and uses less engine retarder than a truck using fixed set speed cruise control. The flexible set speed controller reduced platoon average fuel consumption by 6.0% to 9.0% and platoon average retarder work by 53.9% to 62.1% compared to the fixed set speed controller (Table 5.2). Again, these improvements came at no cost to the trip time. This suggests that the platoon's fuel economy increases by driving the front truck more intelligently using a flexible set speed cruise control which takes advantage of the topography of the road.

For example, Figure 5.1 shows an instance in the simulation where the road transitions from a uphill section to a downhill section and then to another uphill section. As the trucks transition into the first downhill section, the follow truck from the platoon using the fixed set speed cruise control has to use significant engine retarder to maintain the set speed. Conversely, the follow truck from the platoon using the flexible set speed cruise control is allowed to speed up through this section and when it approaches the next uphill section is has higher momentum to reach the crest of the next hill. By adding flexibility to the cruise controller, the platoon uses less engine retarding on the downhill section which leads to using less fuel on the transition to the upcoming uphill section.

TABLE 5.1
Single Truck Simulation Results–Fuel and Retarder

	Cruise Controller	Single Truck Fuel (kg)	Single Truck Retarder Work (MJ)
South Bound	Fixed	16.0	-44.5
	Flexible	14.8	-10.5
North Bound	Fixed	17.5	-33.6
	Flexible	16.5	-09.9

TABLE 5.2
Platoon Simulation Results–Fuel and Retarder

	Cruise Controller	Platoon Average Fuel (kg)	Platoon Average Retarder Work (MJ)
South Bound	Fixed	15.8	-55.9
	Flexible	14.4	-21.2
North Bound	Fixed	17.3	-44.5
	Flexible	16.2	-20.5

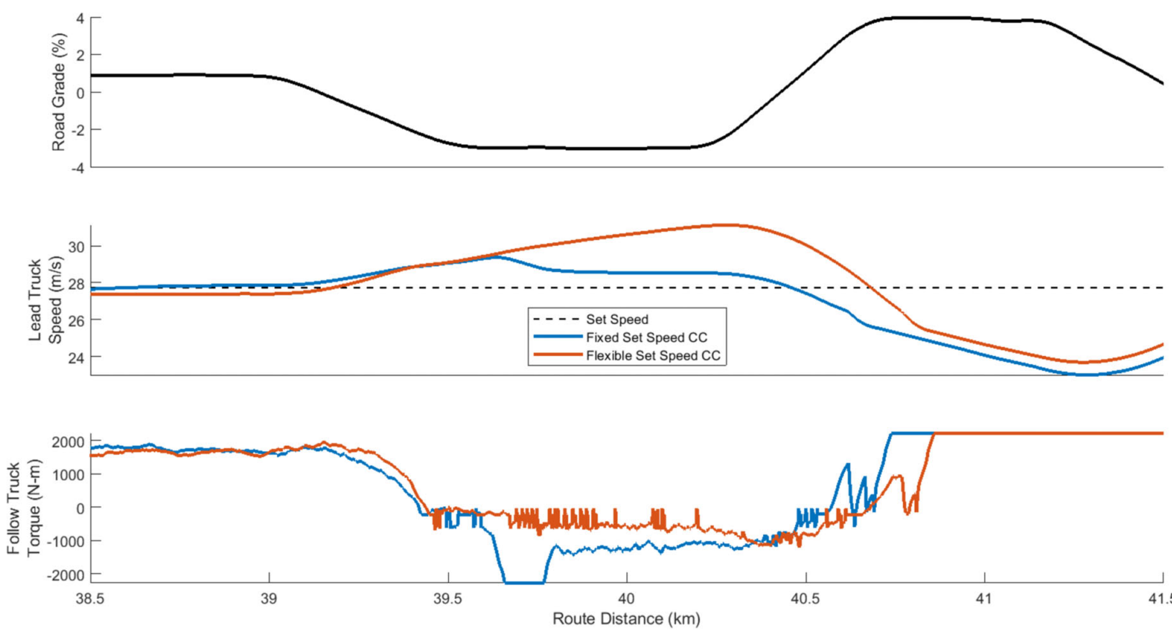

Figure 5.1 Platoon simulation results on a 3 km section.

When comparing to a single truck, the platoons using fixed and flexible set speed cruise control consumed less fuel but used more engine retarder than the respective single truck simulations. The platoon using a fixed set speed showed a 1.1% to 1.4% fuel economy improvement compared to a single truck, and the platoon using a flexible set speed showed a 7.1% to 10.2% fuel economy improvement. But the platoon average retarder work was significantly higher than the single truck retarder work for the fixed and flexible set speed cases. This suggests that further fuel economy improvements could be made by eliminating some of the engine retarding.

Another key aspect of the success of the platoon also depends on how well the nominal platoon gap is maintained. When the platoon gap grows, the aerodynamic benefits of the platoon slightly decrease and, more importantly, the risk of a third party vehicle cutting in between the platoon increases. A detected vehicle cut in causes the platoon to dissolve temporarily. The platoon can be re-engaged once there is no vehicle in between the two trucks, but the temporary platoon dissolution comes at a cost. A vehicle cut in can lead to driver dissatisfaction, and the platoon loses the aerodynamic benefits of the platoon during the temporary dissolution. Therefore, metrics are needed to measure

TABLE 5.3
Platoon Simulation Results–Gap Control

	Cruise Controller	Max. Gap (m)	Cumulative Gap Error (m-s)
South Bound	Fixed	42.3	4,666.1
	Flexible	40.0	3,460.0
North Bound	Fixed	51.5	7,052.8
	Flexible	41.7	4,349.8

the platoon gap maintenance. Maximum gap measures the most significant gap growth event and cumulative gap error (*CGE*) described in Equation 5.1 gives a measurement of the how well the nominal gap is maintained over the route where $d_{desired}$ is the desired platoon gap and d_{actual} is the measured platoon gap.

$$CGE = \int (d_{desired} - d_{actual}\ (t))\ dt$$

(Cumulative Gap Error (CGE)) Equation 5.1

The simulations suggest that a platoon using flexible set speed cruise control on the front truck has better gap maintenance compared to a platoon using fixed set speed cruise control. Table 5.3 shows that the platoon using the fixed set speed has a lower 5.7% to 23.5% lower maximum gap and 35.9% to 62.1% lower cumulative gap error compared to a platoon using fixed set speed cruise control. By adding flexibility to the cruise controller for the fixed set speed cruise controller, it has made it easier for the follow truck to track the front truck.

These results show that platoon fuel economy decreases, platoon retarder work decreases, and gap maintenance improves by using a flexible set speed cruise controller which drives the lead truck more efficiently. Naturally, it is theorized that the platoon fuel economy and gap maintenance can be further improved by driving the front truck more efficiently and in a way that causes the platoon to use less engine retarder. The upcoming section discusses the development and analysis of an MPC strategy that uses look ahead road topography to accomplish this task.

6. LOOK AHEAD MPC STRATEGIES

6.1 Lead Truck MPC

Platoon fuel economy was improved by driving the front truck more efficiently and reducing the platoon retarder work using a commercially available flexible set speed cruise controller on the lead truck, but a flexible set speed cruise controller has limitations as it is purely reactive to the topography changes and there is no predictive look-ahead element. This section will discuss the development and analysis of a predictive cruise control algorithm that uses look-ahead grade data to create an optimal speed profile for the front truck with the expected outcome of improved platoon fuel economy. This strategy will be referred to as long horizon predictive cruise control, or LHPCC, as it uses the grade data for the entire route, rather than a short look-ahead interval, to create an optimal speed profile. The optimized speed profiles were implemented during single truck experimental operation using a Cummins provided functionality that commands the speed profile based on route and GPS location. The experimental speed profile was captured using this method and then fed back in to the two-truck platoon simulation.

Platoon simulation results using the experimental speed profiles demonstrate that LHPCC reduces platoon average fuel consumption and platoon average retarder work compared to a platoon using a fixed or flexible set speed cruise control (Table 6.1). A breakdown of fuel consumption by truck reveals that follow truck consumed less fuel than the lead truck when the platoon used LHPCC (Table 6.2). In comparison, the follow truck consumed more fuel than the front truck when the platoon used a fixed set speed and flexible set speed cruise control.

The additional fuel savings seen from using LHPCC can partly be attributed to reducing the follow truck retarder work. Table 6.3 shows that LHPCC reduced the lead truck retarder work by 2.8% and 35.2% compared to the lead truck from the platoon using a flexible set speed, and significantly reduced the follow truck retarder work, 35.6% to 54.4% compared to the follow truck from the platoon using a flexible set speed.

TABLE 6.1
Platoon Simulation Results–Fuel and Retarder

	Driver Model	Platoon Average Fuel (kg)	Platoon Average Retarder Work (MJ)
South Bound	Fixed	15.8	-55.9
	Flexible	14.4	-21.2
	LHPCC	13.8	-15.6
North Bound	Fixed	17.3	-44.5
	Flexible	16.2	-20.5
	LHPCC	15.6	-10.5

TABLE 6.2
Platoon Simulation Results–Lead and Follow Truck Fuel Consumption

	Driver Model	Lead Truck Fuel (kg)	Follow Truck Fuel (kg)
South Bound	Fixed	15.75	15.90
	Flexible	14.39	14.40
	LHPCC	13.99	13.64
North Bound	Fixed	17.17	17.38
	Flexible	16.16	16.32
	LHPCC	15.85	15.38

TABLE 6.3
Platoon Simulation Results–Lead and Follow Truck Retarder Work

	Driver Model	Lead Truck Retarder Work (MJ)	Follow Truck Retarder Work (MJ)
South Bound	Fixed	-46.8	-65.1
	Flexible	-12.1	-30.4
	LHPCC	-11.7	-19.5
North Bound	Fixed	-35.4	-53.6
	Flexible	-11.5	-29.5
	LHPCC	7.5	-13.4

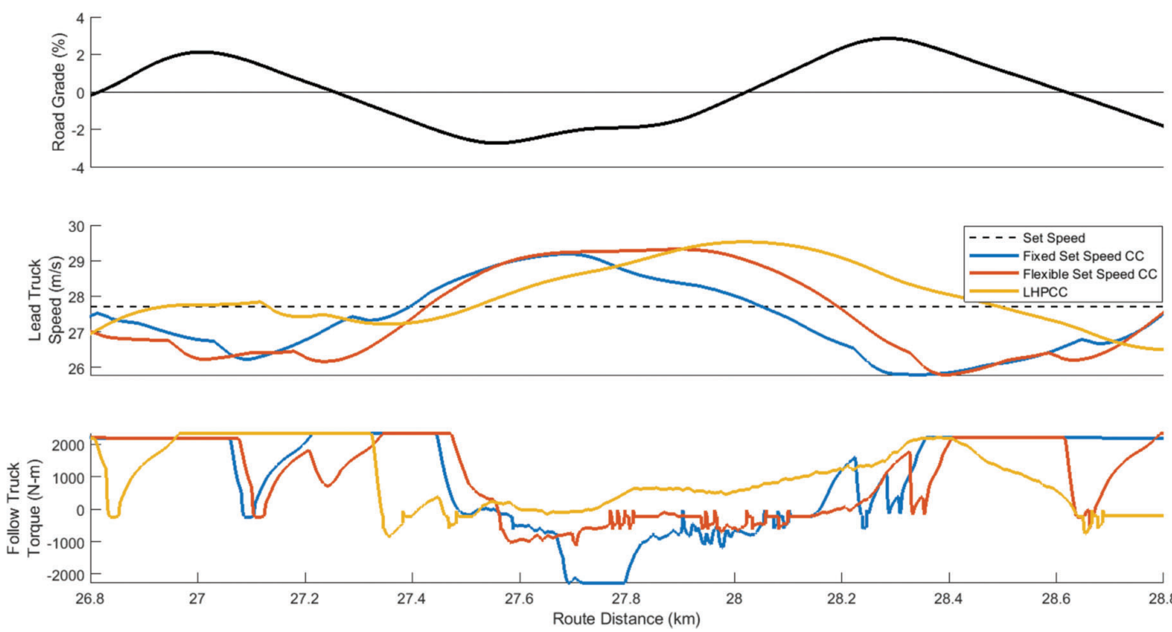

Figure 6.1 Platoon simulation results on a 3 km route.

This reduction in follow truck retarder work is evident in the fuel economy improvements for the follow truck in comparison to the improvements for the lead truck. The lead truck from the platoon using LHPCC only consumed 2.8% and 1.9% less fuel compared the lead truck from the platoon using a flexible set speed while the follow truck from the platoon using LHPCC consumed 5.3% and 5.8% less fuel compared the follow truck using a flexible set speed. Therefore, the follow truck sees significant fuel economy improvements from a smoothly and efficiently driven front truck, LHPCC.

For example, Figure 6.1 shows an instance in the simulation which starts in an uphill section, transitions to a downhill section, and then transitions to an uphill section. Using a fixed set speed cruise control, the follow truck uses significant engine power to maintain the desired platoon gap from the lead truck. Using flexible set speed cruise control, the lead truck is allowed to increase in speed through the downhill section which allows the platoon to conserve momentum entering the uphill section which improves the fuel economy, but LHPCC allows the platoon to operate even more efficiently. As the platoon crests the first hill,

TABLE 6.4
Platoon Simulation Results–Gap Control

	Driver Model	Max Gap (m)	Cumulative Gap Error (m-s)
South Bound	Fixed	42.3	4,666.1
	Flexible	40.0	3,460.0
	LHPCC	30.7	1,739.6
North Bound	Fixed	51.5	7,052.8
	Flexible	41.7	4,349.8
	LHPCC	34.3	2,157.6

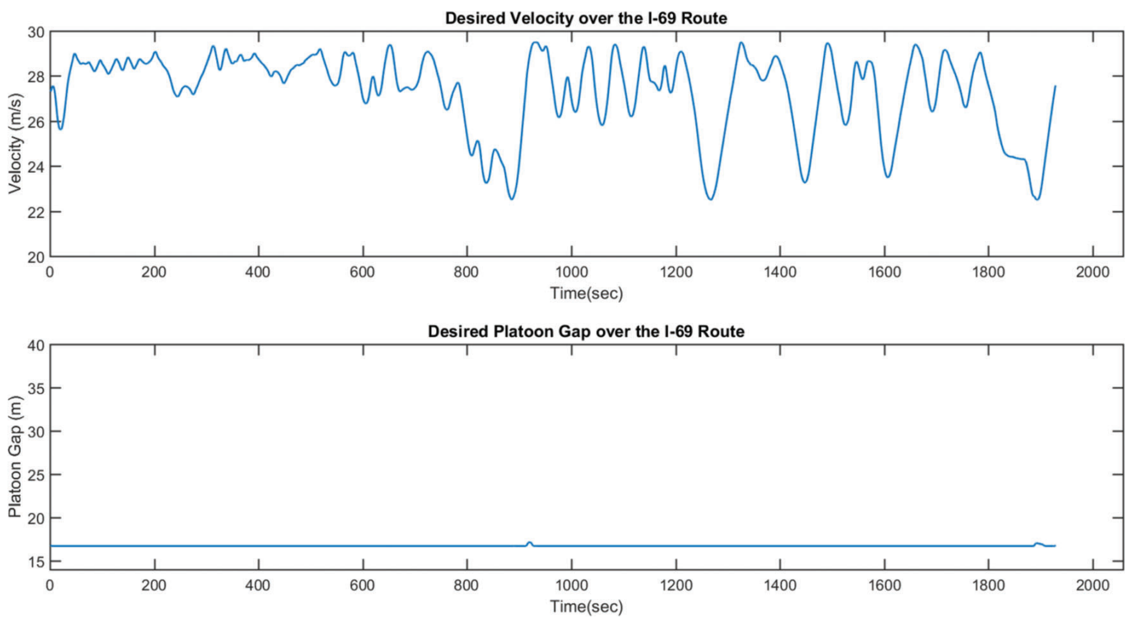

Figure 6.2 Two-truck MPC generated lead and follow truck profiles.

the speed is reduced so that the platoon uses little to no engine retarding on the downhill section. So, the platoon speed is maximized at the bottom of the downhill section and therefore has higher momentum as it enters the uphill section which allows the platoon using LHPCC to conserve fuel.

A look at the maximum gap and cumulative gap error shows that LHPCC significantly improves platoon gap control compared to a fixed or flexible set speed cruise control (Table 6.4). The platoon using LHPCC has a 17.8% to 23.3% smaller maximum gap and a 49.7% to 50.4% smaller cumulative gap error compared to the platoon using a flexible set speed cruise controller. By driving the front truck efficiently, the platoon gap becomes easier to control.

6.2 Two Truck MPC

Previously, platoon gap growth was generally determined to be a negative side effect of a poorly driven front truck, but a small amount of gap growth may be acceptable in certain platoon applications. If an acceptable small gap growth limitation was defined, it can be hypothesized that the platoon fuel economy could be improved if an MPC was allowed to control both the front and follow truck. In order to test this, an MPC was built to generate an optimal lead truck speed profile and an optimal platoon gap profile.

The results from the two truck MPC show that the closest platoon gap is almost always the most optimal if the front truck speed profile can be optimized. Figure 6.2 shows the optimal speed profile for the front truck and the optimal platoon gap. The optimal lead truck speed profile is very similar to speed profile generated from LHPCC. The optimal platoon gap over the route is almost always at the nominal gap of 16.7 m. While the two truck MPC was a useful exercise, it can be concluded that LHPCC paired with a fixed gap platoon is the most optimal for a two-truck platoon on the I-69 route.

7. SYNCHRONIZED SHIFTING

Previously, this paper investigated ways to improve platoon fuel economy and gap maintenance by changing how the front truck is driven. Now, the focus will shift to the development and analysis of a strategy to improve gap maintenance through shifting. While

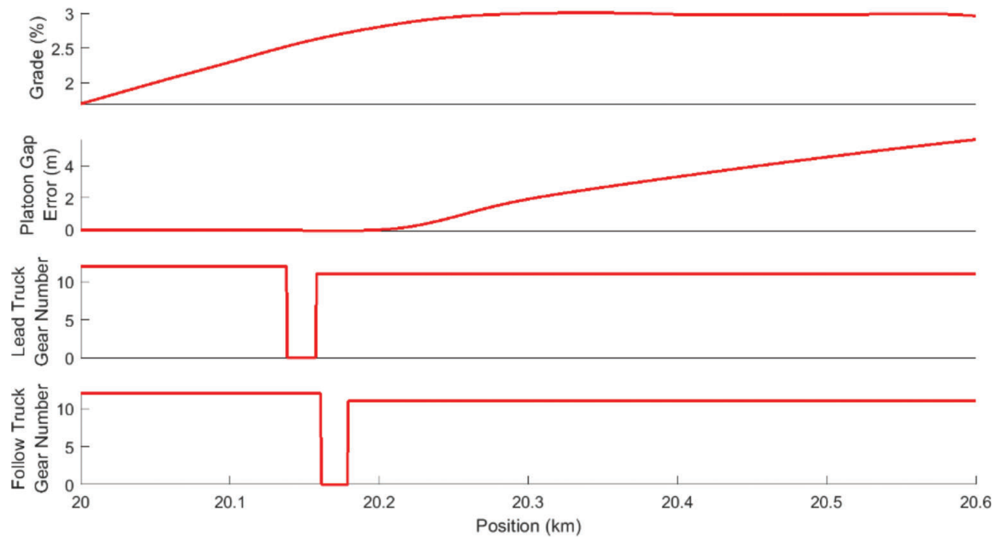

Figure 7.1 Platoon simulation results (without synchronized shifting).

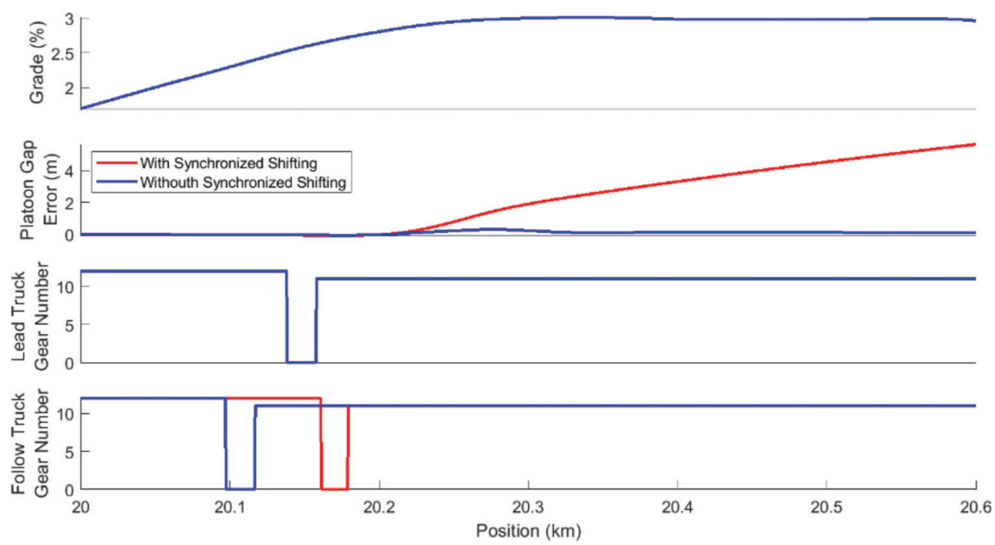

Figure 7.2 Platoon simulation results (with and without synchronized shifting).

LHPCC has shown to improve gap control, there may be reasons that the platoon would either want to further improve gap control for while using LHPCC or may want better gap control while using a fixed or flexible set speed cruise controller.

Figure 7.1 shows a section of the route from the north bound platoon simulation using a flexible set speed cruise control. In this section, the trucks are on a steep uphill section as noted by the nearly 3% grade. The lead truck shifts from 12th gear around 20.14 km, to neutral (0), and then to 11th gear around 20.16 km. Because the lead truck has more torque available in the lower gear, the lead truck begins to pull away from the follow truck. In order to maintain the desired platoon gap, the follow truck begins to shift from 12th gear shortly after 20.16 km, to neutral (0), and then to 11th gear around 20.18 km. But by this time, the lead truck has already started to pull away from the follow truck, the gap growth becomes noticeable around 20.2 km. The gap continues to grow until the follow truck is nearly 12.7 m farther back from the desired platoon gap. This example of gap growth can lead to driver discomfort or vehicle cut-ins. Therefore, instead of shifting the follow truck based solely on commanded torque, it is hypothesized that platoon gap control can be improved by shifting the follow truck with the front truck.

So, the simulation framework was adjusted so the follow truck shifts when the lead truck shifts. Going back to the example shown in Figure 7.1, the platoon gap control is improved with synchronized shifting as seen in Figure 7.2. By shifting both vehicles at the same time, the gap growth event is mitigated.

Comparing the north and south bound average simulation results with and without simultaneous shifting, it is evident that simultaneous shifting improves platoon gap control as seen in Table 7.1. Adding synchronized

TABLE 7.1
Platoon Simulation Results–Gap Control (with and without Synchronized Shifting)

	Driver Model	Average Max Gap (m)	Average Cumulative Gap Error (m-s)
Without Synchronized Shifting	Fixed	46.9	5,859.5
	Flexible	40.9	3,904.9
	LHPCC	32.5	1,948.6
With Synchronized Shifting	Fixed	31.9	1,845.0
	Flexible	30.3	1,428.6
	LHPCC	22.2	517.3

TABLE 7.2
Platoon Simulation Results–Fuel Consumption (with and without Synchronized Shifting)

	Driver Model	Average Fuel Consumed (kg)
Without Synchronized Shifting	Fixed	16.55
	Flexible	15.32
	LHPCC	14.71
With Synchronized Shifting	Fixed	16.56
	Flexible	15.32
	LHPCC	14.68

shifting reduces average maximum gap by 25.9% to 32.0% and average cumulative gap error by 63.4% to 73.5%.

Additionally, these gap control improvements come at little to no negative impact on fuel consumption, seen in Table 7.2, or trip time. The absolute percent difference in fuel consumption with and without synchronized shifting is less than 0.25%. Because the lead truck does not change in either simulation with or without synchronized shifting, there is no change in trip time.

8. CONCLUSIONS

This analysis looked at different strategies for driving a front truck in a two-truck heavy duty platoon and one shifting strategy. These strategies were aimed at improving platoon fuel economy and platoon gap control on hilly terrain without increasing trip time. A comparison of the front truck driver strategies shows that LHPCC offers the highest protentional for fuel savings and best gap control on hilly terrain. Driving the front truck rigidly and inefficiently, as was the case for a fixed set speed cruise controller, has a compounding negative effect on the follow truck. The follow truck has to use significant engine braking and fueling in order to maintain a constant platoon gap. Conversely, driving the front truck smoothly and efficiently, as was the case for the LHPCC, leads to a significantly more efficient use of fuel for both trucks as seen in Figure 8.1. While

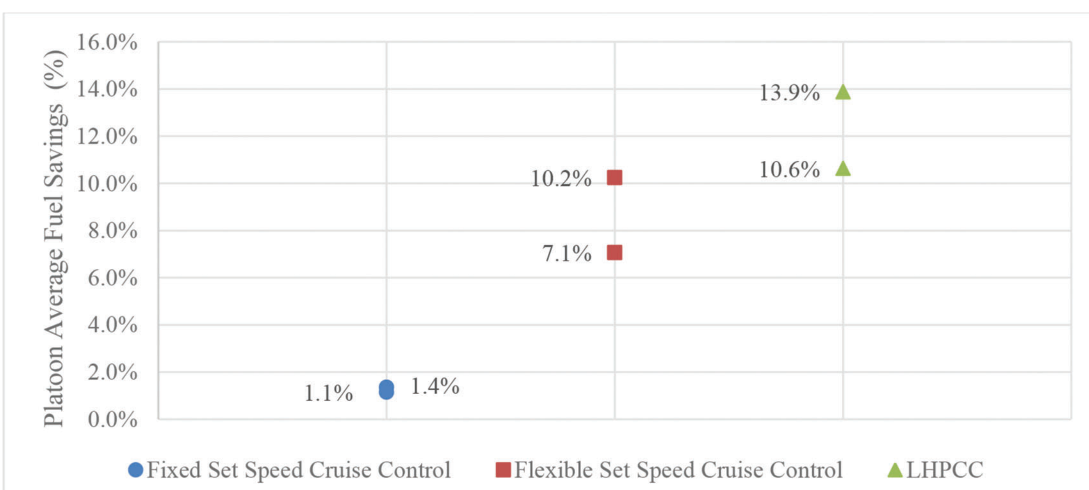

Figure 8.1 North and south bound fuel savings in comparison to a single truck using a fixed set speed cruise controller.

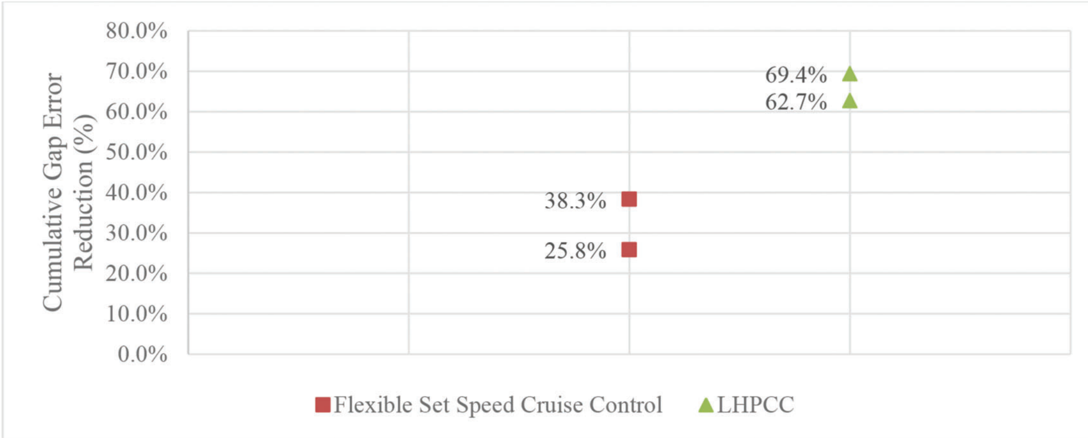

Figure 8.2 North and south bound cumulative gap error reduction in comparison to respective fixed set speed cruise control cumulative gap error.

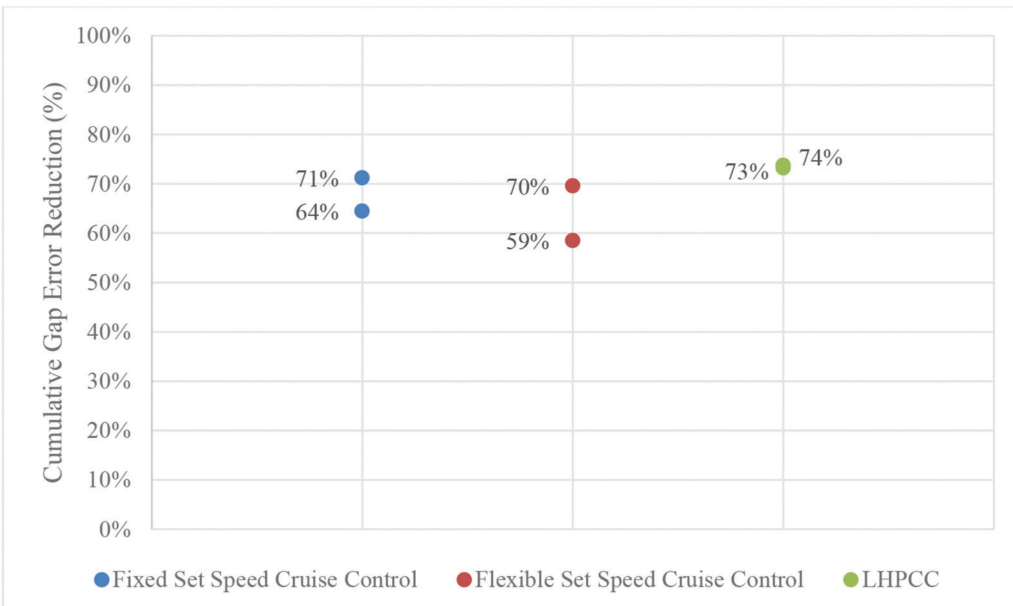

Figure 8.3 North and south bound IN I-69 cumulative gap error reduction using synchronized shifting in comparison with not using synchronized shifting.

LHPCC sees the high fuel savings, significant fuel savings can even be achieved using a flexible set speed cruise controller. Additionally, driving the front truck more efficiently leads to better gap control. Figure 8.2 shows that using a flexible set speed cruise control significantly reduces cumulative gap error (CGE) and using LHPCC reduces CGE even more.

The improvements seen from LHPCC led to the investigation of a two-truck MPC approach. The two-truck MPC results for this route indicate that the front truck should use an optimized route and the follow truck should maintain a nearly constant platoon gap. Because a two-truck MPC algorithm is more computationally expensive than a single truck MPC algorithm, a LHPCC strategy on the front truck with a constant platoon gap target is sufficient rather than using a two-truck MPC strategy.

Lastly, a synchronized shifting strategy was tested in the simulation framework with all three front truck driver strategies. Synchronized shifting significantly improved platoon gap control in each case without increasing trip time or significantly affecting fuel consumption as seen in Figure 8.3.

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APPENDICES

Appendix A. Purdue-Developed/INDOT-Approved Safe Truck Platooning Testing Protocol

APPENDIX A. PURDUE-DEVELOPED/INDOT-APPROVED SAFE TRUCK PLATOONING TESTING PROTOCOL

- High-Efficiency Control Systems for Connected Class 8 Trucks, 2019 Work Truck Show, March 6th, 2019
- Commercial Vehicle Research at Purdue, Alumni Event hosted by GM, Detroit, April 14th, 2019
- Class 8 Truck Platooning, 2019 MAASTO
- Class 8 Truck Platooning, 2019 SAE COMVEC, Sept. 10th, 2019
- Advancing Driver-Centric Automation to Enhance Safety and Efficiency in Freight Trucking, June 2020 https://www.youtube.com/watch?v=2Af30A67W1A
- JTRP & Road School Presentations and Posters

Formstack Submission For: Indiana Vehicle Platooning
Submitted at 03/13/20 5:10 PM

Company Name:	Purdue University
USDOT#:	413654
Name (Primary Authority Contact)*:	Greg Shaver
Phone (Primary Authority Contact):	(765) 491-6052
Email (Primary Authority Contact):	gshaver@purdue.edu
Name (Field Representative):	Ryan Thayer
Phone (Primary Authority Contact):	(812) 350-8975
Email (Primary Authority Contact):	thayer7@purdue.edu

Indiana Route(s) of Operation (include directional for two way trips):	Route 1: https://goo.gl/maps/VtBfQDg9KnpUdbz46 – 57 min (57.4 miles) via US-52 E Start: Junction of Veterans Memorial Pkwy E to US-52 S Lafayette, IN 47905 • Head southeast on US-52 E 26.4 mi • Use any lane to take the ramp onto I-65 S 1.9 mi • Take exit 140 for IN-32 toward Lebanon/Crawfordsville 0.2 mi • Turn left onto IN-32 E/W South St 0.2 mi Halfway: W South St Lebanon, IN 46052 • Head northwest toward W South St 0.2 mi • Merge onto I-65 N 1.3 mi • Take exit 141 for US-52 W 0.8 mi • Continue onto US-52 W 26.5 mi End: Junction of Veterans Memorial Pkwy E and US-52 S Lafayette, IN 47905 Route 2: https://goo.gl/maps/APD5sut3oWwRSHFU7 – 51 min (56.8 miles) via I-65 S Start: I-65 S from IN-38 Lafayette, IN 47905 • Head south on I-65 S 28.1 mi • Take exit 140 for IN-32 toward Lebanon/Crawfordsville 0.2 mi • Turn left onto IN-32 E/W South St 0.2 mi Halfway: W South St Lebanon, IN 46052 • Head northwest toward W South St 0.2 mi • Merge onto I-65 N 28.1 mi End: I-65 N and IN-32 Lafayette, IN Route 3: https://goo.gl/maps/XMW1UpBrqJHWbBzG6 – 1 h 32 min (107 miles) via I-69

	Start: W Fullerton Pike to S I-69 Bloomington, IN 47403 • Head southeast on I-69 0.8 mi • Keep left to stay on I-69, follow signs for Evansville 52.1 mi • Take exit 62 for U.S. 50/U.S. 150 toward Washington/Vincennes 0.5 mi • Keep left at the fork, follow signs for Loogootee 148 ft Halfway: US-50 Washington, IN 47501 • Head south on US-150 E/US-50 E toward US-150 E/US-50 E 0.3 mi • Turn left onto the Interstate 69 N ramp 0.4 mi • Merge onto I-69 52.9 mi End: W Fullerton Pike Bloomington, IN 47403
Start Date:	Mar 23, 2020
End Date:	May 22, 2020
Checkbox:	Mon Tues Wed Thur Fri Sat Sun
Estimated Hours of Operation:	Up to 9 hours per day. No more than 4 days of testing in a given week is anticipated.
Number of vehicles in the platoon:	2
VIN number of vehicles in platoon:	• 1XPBD49X2KD631444 • 1XPBD49X2KD631445

Number of overall vehicles equipped as part of activity:	Three Class 8 tractor trailers; Two equipped with Platoon Pro hardware/software (Platooning Trucks); One standard equipped from factory (Control Truck)
Unique Vehicle Markings (if any or none):	Purdue University #9488 & 9489
Hazardous materials?:	No
Please specify:	
***Your notification must include a detailed plan for general platoon operations for your company's proposal. This entry should address contributing technologies to be used, safety validation, operational design domain, platoon formation method, platoon dissolution method & fallback, and vehicle description:**	Testing Modes (1) Standard Platooning–Use Peloton's PlatoonPro* system to maintain a ~55 ft gap while the front truck is being operated with standard cruise control. This approach has already been tested on a closed track in Texas and on-road in California. (*see Peloton's PlatoonPro Safety Report at https://peloton-tech.com for additional details) (2) Lead Truck use of Long-horizon Predictive Cruise Control (LHPCC)–Use Peloton's PlatoonPro* system to maintain a ~55 ft gap while the front truck uses a conventional cruise control system to track a pre-determined variable velocity set-point. This technology has already been tested on a closed track in Texas. (3) Variable Gap Platooning–Use Peloton's PlatoonPro* system together with a Purdue/Peloton-developed gap tracking controller. This technology has already been tested on a closed track in Texas. (4) Synchronized Shifting–Use Peloton's PlatoonPro* system to maintain a ~55 ft gap while a Purdue/Peloton-developed rear truck shifting controller enables simultaneous shifting. This technology has already been tested on a closed track in Texas.

For all of the above testing scenarios, Peloton's PlatoonPro* system will safely dissolve the platoon if: a 3rd party vehicle cut in is detected, the gap exceeds a distance of 80 ft, the gap drops below a pre-set threshold, either driver exits cruise control, either driver disengages the PlatoonPro system, either driver applies the brakes, one of the trucks exits an approved geofenced platooning location, or if the E-stop installed on the dashboard is engaged.

Vehicle Descriptions

Truck 1
• Make: Peterbilt
• Model: 579
• Year: 2019
• VIN: 1XPBD49X2KD631444
• Plate #: 683
• Color: White
• Truck #: 9488

Trailer 1
• Make: Wabash National
• Type: Dry Box Van Trailer
• VIN: 1JJV532D9LL204587
• Plate#: 9301899
• Length: 53’

Notes: 80-inch sleeper with 53-ft. box trailer weighted to 65,000 lbs.

Truck 2
• Make: Peterbilt
• Model: 579
• Year: 2019
• VIN: 1XPBD49X2KD631445
• Plate #: 684
• Color: White
• Truck #: 9489

	Trailer 2 • Make: Wabash National • Type: Dry Box Van Trailer • VIN: 1JJV532D4KL166586 • Plate#: SP809CRS • Length: 53' Notes: 80-inch sleeper with 53-ft. box trailer weighted to 65,000 lbs. Truck 3 (Control truck) • Make: Peterbilt • Model: 579 • Year: 2018 • VIN: 1XPBD49X5KD264300 • Plate #: 74469X • Color: White • Truck #: 9489 • Trailer VIN: Trailer 3 • Make: Wabash National • Type: Dry Box Van Trailer • VIN: 1JJV532D2KL166585 • Plate#: SP808CRS • Length: 53' Notes: 80-inch sleeper with 53-ft. box trailer weighted to 65,000 lbs.
File:	View File
Submitter Name:	Greg Shaver
Title:	Professor of Mechanical Engineering
Phone:	(765) 491-6052
Email:	gshaver@purdue.edu

About the Joint Transportation Research Program (JTRP)

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

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

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

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

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