Alberta Motor Transport Association

Cooperative Truck Platooning Systems Trial

Final On-Road Trial Report

June 30, 2022

Contents

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Document Purpose

This document provides details of on-road trial including test matrix, test routes, sensors and instrumentation, data acquisition system and analysis of the trucks' testing results.

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1. Introduction

A truck platoon is two or more electronically connected trucks that form a “road train”. The term “cooperative” platooning refers to the cooperation between lead and follower trucks that the data is continuously transmitted from the lead truck (relative location, speed, acceleration) to the follower truck to allow optimum braking and acceleration for the follower truck.

The Alberta Motor Transport Association (AMTA), in collaboration with Alberta Transport, Bison Transport, Pronto and University of Alberta, conducted cooperative truck platooning trials on public roads in order to study i) passive fatigue driver behavior and interaction with advanced driver assistance system (ADAS) including platooning, ii) fuel-consumption, iii) tailpipe emissions including greenhouse gas reduction, and impacts on criteria air pollutants, and iv) traffic flow interactions and operational factors. This document provides details of the test matrix, test routes, sensors and instrumentation, data acquisition system and data analysis for fuel consumption, emissions, and platooning performance.

A total of 41 trips on Highway 2 in Alberta were conducted between January 12, 2022 and January 30, 2022 that covered the typical Canadian winter season. The test matrix includes a fixed number of controlled variables (CVs) shown in blue labels in Figure 1. The main CVs are drivers, and the truck operating mode (manual vs using ADAS), platooning distance (measured as the time gap between two trucks) and route. Non-controllable variables (NCVs) are shown in red labels in Figure 1, and were collected during the trials. They are used in the post-processing and analysis of the collected data. These include vehicle engine parameters, road conditions, weather conditions, traffic conditions, cargo weight and trailer configuration.

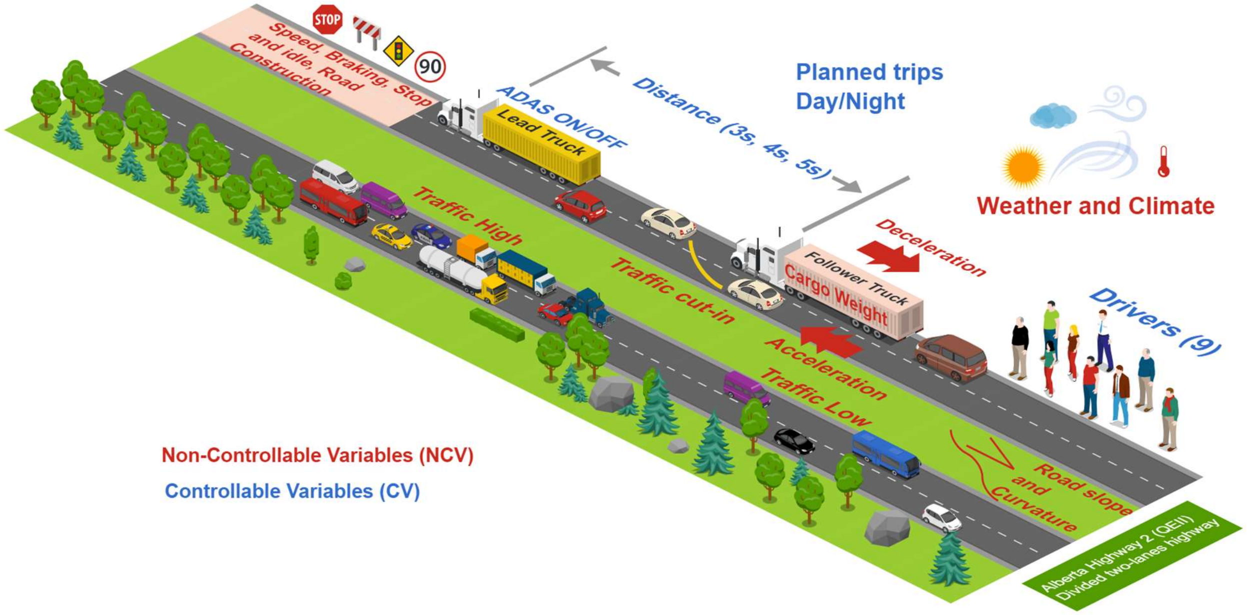


Figure 1: Diagram of the platoon test matrix controllable variables (CVs) in blue and non-controllable variables (NCVs) in red

Table 1 shows a list of four CVs for the on-road platooning trials conducted in January 2022. Appendix A includes details of each trip conducted during trials.

Table 1: Controlled variables and road segments

Road Segment (Road ID)	Drivers	Platoon Separation Distance (commanded value)	Use of ADAS by trucks
Edmonton – Calgary (ID: 1)	9 individuals	3 sec 4 sec 5 sec	Yes No
Calgary – Edmonton (ID: 2)			

Table 2 shows a list of NCVs and levels considered for each variable.

Table 2: Non-controllable variables (NCVs) recorded for each test/segment

Weather Conditions[†]	Road Condition[†]	Visibility[†]	Trailer	Cabin Temperature /Comfort[§]	Cabin CO_2
• Sunny • Rain • Freezing rain* • Low wind • Strong wind* • Snow* • Fog*	• Bare dry • Bare wet • Partly snow covered • Covered snow* • Icy, black ice*	• Low* • High	• Weight • Distance between truck tractor & trailer • Configuration: Dry, Refrigerated	• Normal • Too warm • Too cold	• Normal[‡] • High

* No platooning permitted due to safety

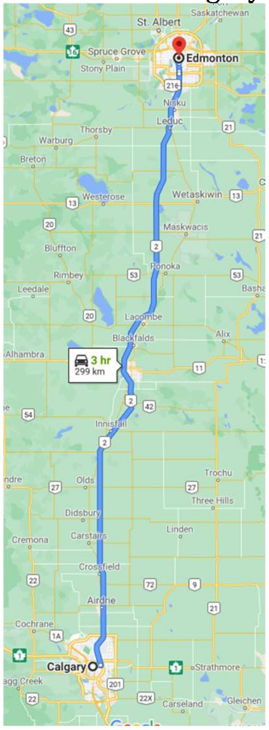
[†] Definition based on https://511.alberta.ca/about/tutorial, see Appendix B.

[§] Using ASHRAE Standard 55 for classifying thermal comfort

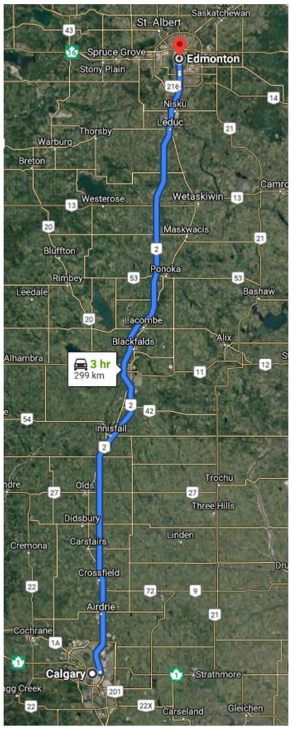
[‡] 1200–1300 ppm of CO_2 based on ASHRAE standard

2. Test Route

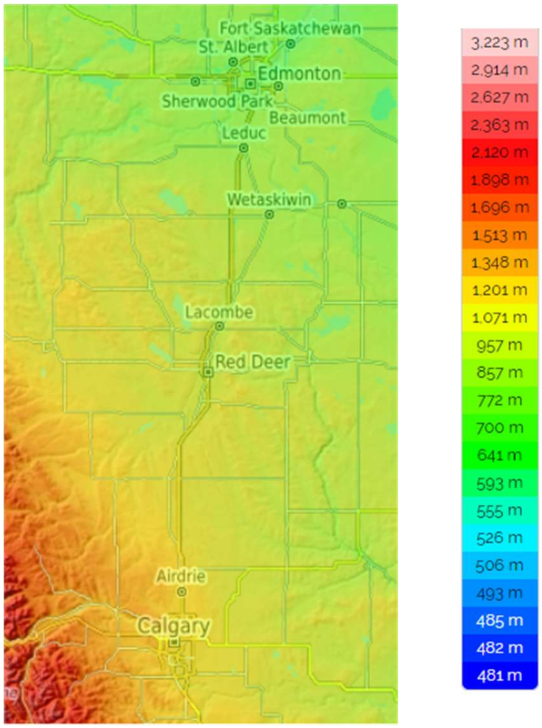
On-road trials were conducted on Highway 2 between Calgary and Edmonton. The designated Hwy-2 route for the trial is a predominately 4-lane divided highway with relatively low grades and long straight sections. Platooning was aimed for a portion of Highway 2 between Airdrie and Leduc with a distance of 234 km. Figure 2 shows details of the testing route on Highway 2 between Edmonton and Calgary in central Alberta.



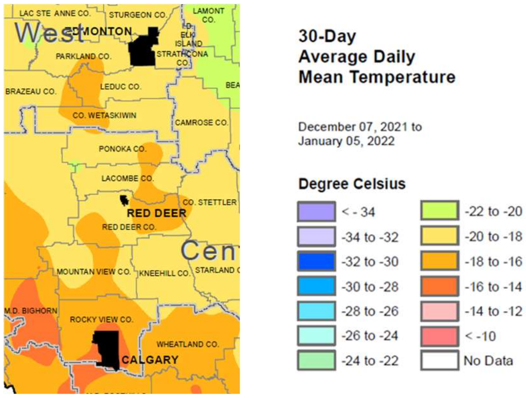
Driving map



Satellite view

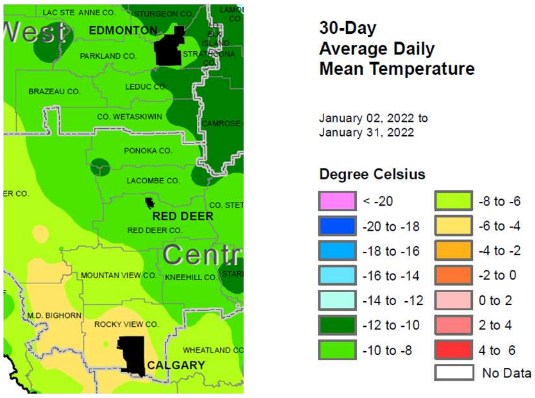


Topography and elevation



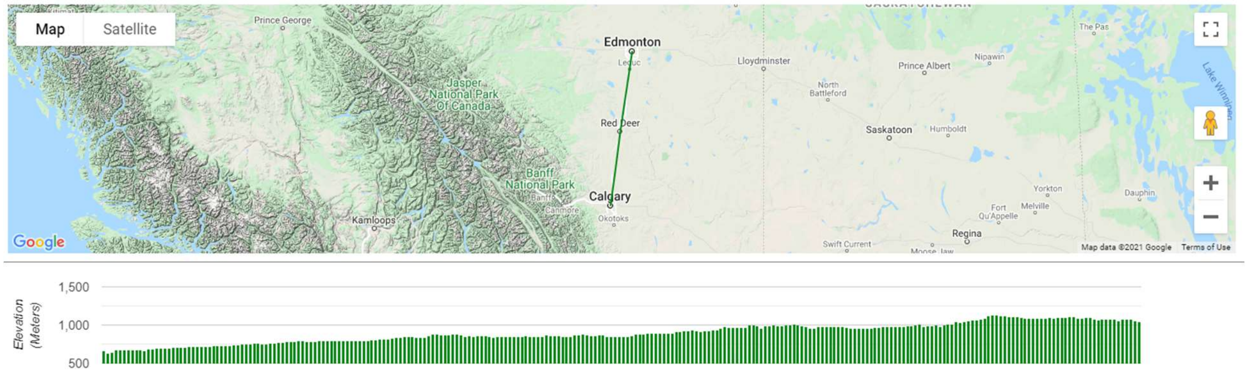
Temperature, December 2021

(Alberta Agriculture)



Temperature, January 2022

(Alberta Agriculture)



Elevation gain from Edmonton (left) to Calgary (right) obtained from Distanceto.com

Figure 2: Highway 2 Edmonton- Calgary (QEII) map, topography, temperature, elevation

The elevation of Edmonton is 670 meters and the elevation of Calgary is 1, 048 meters, which is a difference of 378 meters. The average slope along the road is 1.3 m per km. Via round trips, trucks' data was collected on both directions as the uphill and downhill road grades have impacts on vehicle tractive power (among many other variables).

3. Truck and Engine

3.1. The Truck

Both vehicles used in the study are Peterbilt 579 trailer tractor class 8 trucks, model year 2019. Images of a Peterbilt 579 truck tractor and a sample of Bison Transport trailer are shown in Figure 3.

Figure 3: A picture of Peterbilt 579 truck tractor and the trailer by Bison Transport

The transmission is Eaton Automated, front axle 12,000 – 14,600 lbs., Hendrickson front springs, Peterbilt front Air Leaf, rear axle, Meritor rear suspension and Peterbilt Flex Air.

Truck Dimensions

Our team measured and recorded the dimensions of the trucks. As shown in Figure 4, the width of the tractor (measured the front bumper) is 2.40 m, and the height of the tractor (measured from the roof top to the ground) is 3.26 m. The total length of the truck (tractor and trailer) is 22.85 m, and the height of trailer (measured from the trailer top to the ground) is 4.14 m. Furthermore, the wheelbase of the trailer is 1.28 m, and the gap between the tractor and trailer is 1.13 m. The shape and dimensions of the truck affects the air drag and fuel consumption of the trucks.

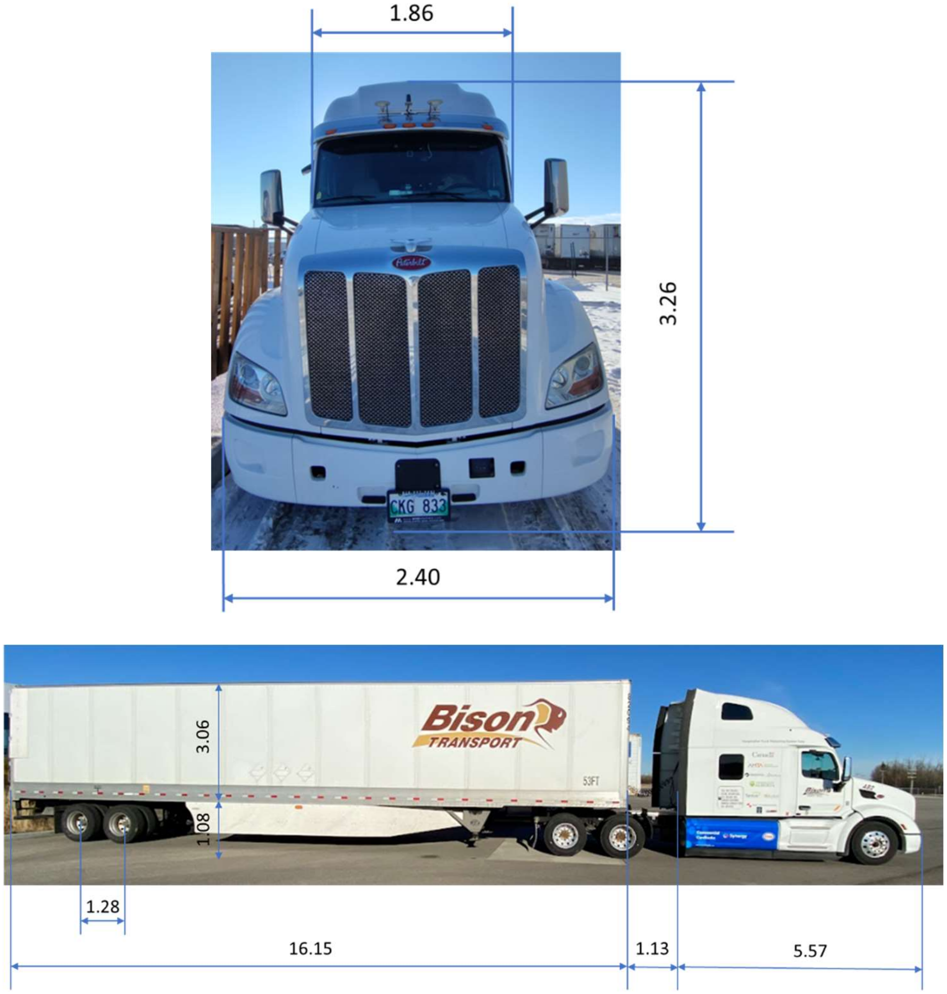


Figure 4: Truck dimensions. Values are in meter.

Cooperative Truck Platooning System

In this project, the platoon included two class-8 trucks equipped with Cooperative Truck Platooning Systems (CTPS), consisting of radar, cameras, GPS, vehicle to vehicle communication, and other sensors, as shown in Figure 5. The GPS provided accurate positions of the trucks, and the LTE antenna allowed two trucks to communicate with each other and convey important information for platooning. The forward-facing camera on the windshield was responsible for detecting objects (e.g., vehicles, lane markings, etc.), and the driver-facing camera was used to monitor the driver behavior for attentiveness. The radar in the front bumper was employed to detect vehicles in front of the host vehicle and measure the distance between the truck and vehicles. Furthermore, the sensor fusion between the forward-facing camera and the radar was used to provide accurate estimation of the distance between two trucks. Figure 5 shows the two trucks during cooperative platooning operation.

Figure 5: Equipment and sensors used to enable cooperative truck platooning

3.2. The Engine and Exhaust Aftertreatment System

The truck engine is the Cummins ISX15, 15L certified according to US EPA Tier III emission regulations of 2017. Engine power, torque, and speed specifications are shown in Figure 6.


cummins.com

Rated power, 321-451 hp
Peak torque, 2237-2779 Nm
Max speed, 2000-2100 rpm
6 cylinders

Figure 6: Cummins X15 engine in the Peterbilt 579 truck

The engine maximum fuel consumption rate is 1.3 liter/min. The engine features include:

- VGT Turbocharger – A reliable and precise design for rapid acceleration
- XPI Fuel System – High pressure enables multiple injection events per cycle for industry-leading fuel economy and quieter operation
- Single-Module™ Aftertreatment System – A compact and lightweight system that offers increased ash capacity and extended maintenance intervals
- High-Capacity Electronic Control Module (ECM)
- Cummins Engine Brake – up to 600 braking hp

According to the regulation, the emission certification limit values for the engine are:

- Non-methane HC (NMHC), 0.14 g/bhp-hr
- NOx, 0.2 g/bhp-hr
- PM, 0.01 g/bhp-hr
- CO 15.5 g/bhp-hr

The two engines on two Peterbilt trucks are US EPA 2017 emission certified, GHG 2020 Model Year certified, and CARB certified. Table 3 summarizes engine identifications and certifications.

Table 3: Engine IDs, models, and certifications

	Engine 1- Lead Truck	Engine 2 – Follower Truck
Model	Cummins ISX15 Performance	Cummins ISX15 Performance
ENG#	80133363	80133364
Family	KCEXH0912XAW	KCEXH0912XAW
MY	01/19 X15 450ST	01/19 X15 450ST
EPA	US EPA 2017	US EPA 2017
GHG Family Name	LPCR2TRAC8SH	LPCR2TRAC8SH
GHG Regulatory Subcategory	C8HRSTRAC	C8HRSTRAC

3.3. Trailer Configuration

The trailer type directly affects aerodynamic shape and drag losses of a truck. All the trailers in on-road trials were dual tandem axle[1]. The trailers had side skirts (Transtex E-2330T), as shown in Figure 7 with the specifications listed in Table 4.

Figure 7: E-2330T side skirt model that was used in trailers for on-road trials in Alberta. The lower image is from transtex-llc.com.

Table 4: E-2330T side skirt specifications

Model	E-2330T
Application	53 ft. Dry Vans & Reefers
Length	23 ft.
Height	30 in.
Weight	157 lbs including Brackets and Hardware

Goods that were included in the trailer cargo for the trips on Highway 2 were mainly retail products along with some paper products and supplies directed to warehouses. They were dry and temperature-controlled materials. It should be noted that the HVAC of the refrigerated trailers were powered by a separate fuel reservoir on-board the trailer and had negligible aerodynamic impact.

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[1] Exceptions in two trips:
Jan 14 Calgary-Edmonton: triaxle trailer without skirts; Jan 27 Edmonton-Calgary: triaxle trailer.

All Bison Transport trailers run on SmartWay (low rolling resistance) certified tires.

4. Data Collection

This project required cross-functional collaboration with Alberta Transport, NRC, Pronto, Human Factor & Traffic Teams, Bison Transport, Parks Canada and Esso for collecting the required data. Figure 8 shows the interaction with different institutions and the data collected for analysis of the on-road test results.

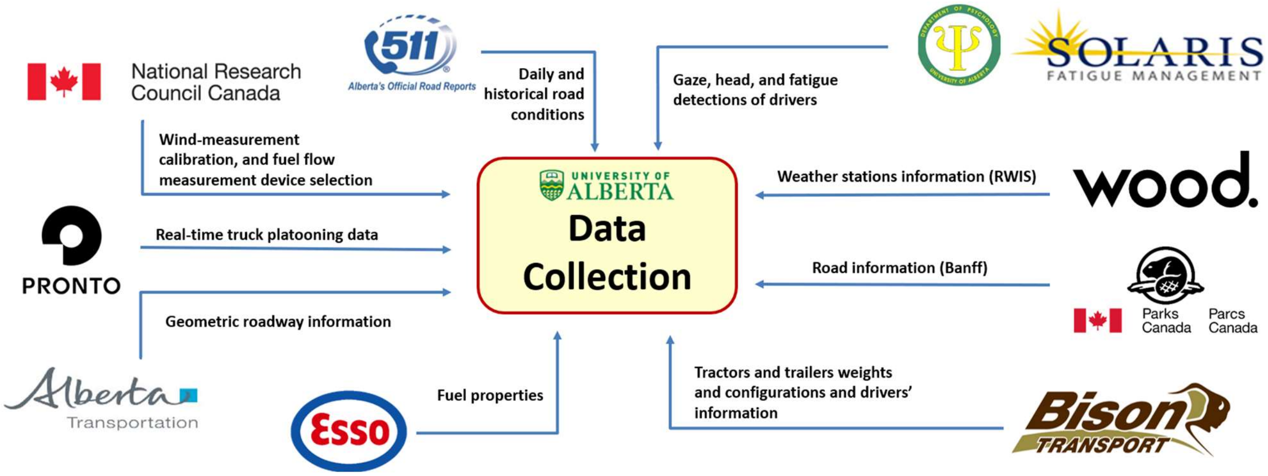


Figure 8: Cross-functional data collection and type of collected data from 9 different institutions

4.1. Instrumentation

A custom-designed Integrated Central Data Acquisition System (ICEDAQ) was designed and built for this project. Given the complexity and varieties of all signals from various subsystems, a flexible ICEDAQ ensures data collection at the desired sampling rate. It includes safeguarding data, remote live monitoring of the system, and multiple data recording capabilities. After designing several options and reviewing various commercial products, an approach from Dewesoft® was selected for the ICEDAQ. The ICEDAQ collects, saves, and time-synchronizes data from various subsystems in a unified, integrated central system. The system provides storage capacity for long return trips with backup plans. The system was installed in both the lead and the follower truck, and the data between the two ICEDAQ systems were synchronized through a GPS PPS time signal. The ICEDAQ in the follower truck was more comprehensive and collects most of the data. Table 5 provides a list of the main signals collected by ICEDAQ. It also includes other data subsystems with alternative data acquisition systems.

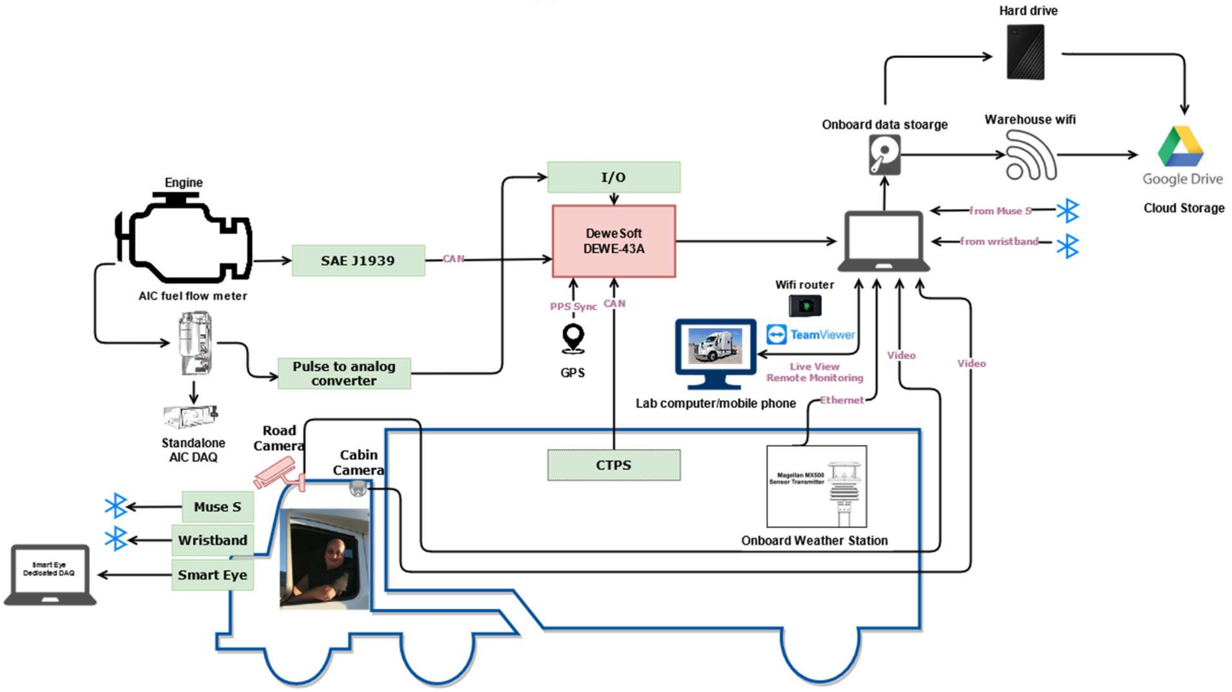
Table 5: List of subsystems generating data for ICEDAQ and other data acquisition systems

Subsystem	Output	Data Acquisition
ADAS	Platooning parameters on Pronto CAN bus	ICEDAQ
Fuel consumption	AIC flow sensor pulse signal converted to analog input	ICEDAQ
Fleet management and trip/driver general data	Omnitracs fleet management and engine OBD II	Omnitracs website

Emissions	CAN output (whenever possible)	ICEDAQ
Cabin HVAC	Wi-Fi	ICEDAQ
Vehicle, powertrain, and drivetrain	SAE J1939	ICEDAQ
Weather	Weather station output on ethernet	MicroServer
Road geometry	Alberta Transport road data – offline	N/A
Road surface	Alberta Transport 511 website – offline	N/A
Traffic environment	Front facing camera feed	ICEDAQ
Cabin status	Cabin camera feed	ICEDAQ
Steering wheel, vehicle dynamics	Pronto CAN bus	ICEDAQ
Driver behavior	Muse S headband to monitor Electroencephalogram	Data acquisition via a smart phone
	Smart Eye tracking	Dedicated data acquisition

A schematic of the ICEDAQ and subsystems are provided in Figure 9. The main aim of the ICEDAQ was to synchronize as much as data possible from different devices by using a centralized DAQ framework.

(a) Lead Truck



(b) Follower Truck

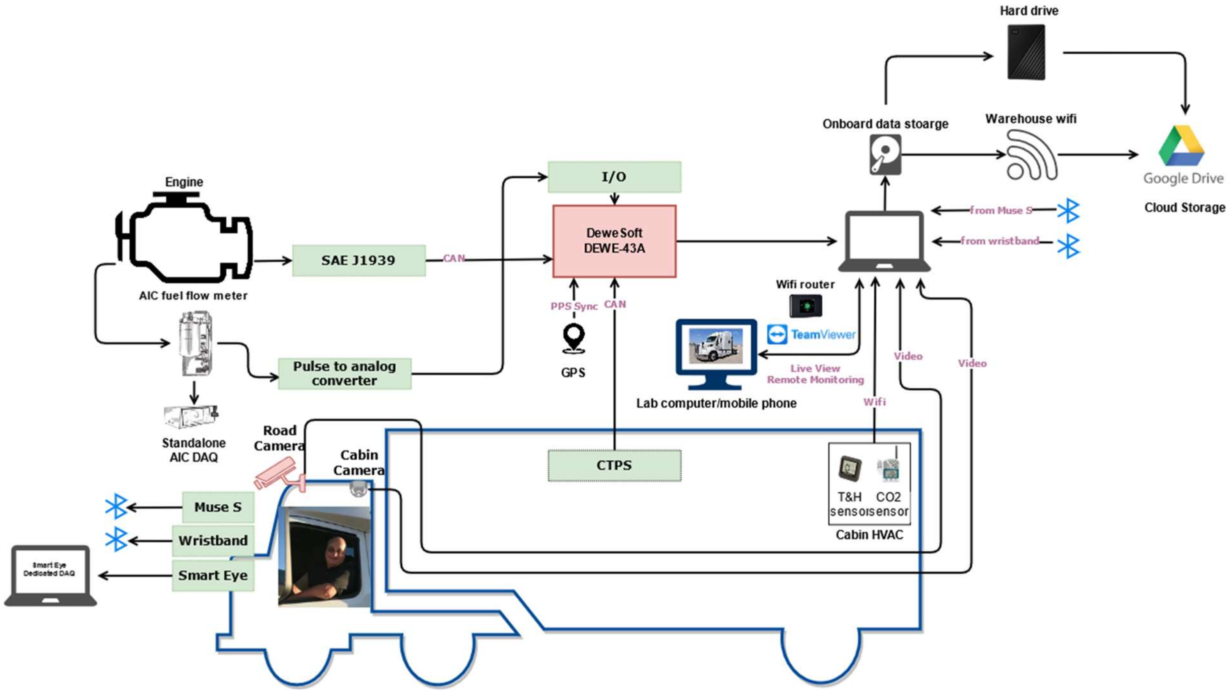


Figure 9: Schematic of ICEDAQ and all subsystem interfaces on the lead and the follower trucks

Specifications of the ICEDAQ are listed in Table 6.

Table 6: Specification of the Main ICEDAQ Components

ICEDAQ Component	Specification
EDU-DS-43A DS-43A USB data acquisition unit	8 channels of voltages or full bridges (9-pin DSUB on front) voltage input ranges: +/-10 mV, +/-100 mV, +/-1 V, +/-10 V, bridge sensitivities: +/-1, +/-10, +/-100, +/-1000 mV/V (@10 V excitation), A/D converter: 24-bit resolution with anti-aliasing filter, 204.8 kS/s sampling rate per channel DSI adaptor supported - 8 Synchronized REAL TIME COUNTER (7-pin LEMO on front) - 2x CAN 2.0b BUS isolated (9-pin D-SUB on front) - 2x Sync port (4-pin LEMO on back) - 1x Power In (9-36 VDC needed) (2-pin LEMO on back) (external AC supply incl.) - 1x GND port (Banana plug on back)
DEWESoft-OPT-NET	DEWESoft Network data acquisition including remote control allows complete remote-controlled setup as well as forwarding the raw data of selected channels via a network connection
DS-GPS-SYNC	10 Hz GPS antenna/receiver with pps and NMEA protocol. - Connects to USB interface for absolute time information and - L1B4m standard sync connector for pps signal, 5m cable. - Fits to DS-43A, SIRIUS.
DS-PORTABLE-CONTROLLER DEWESoft Controller	17” Display - Intel i7 - 32GB RAM - 500GB Internal SSD - 2TB Internal SSHD - Windows 10

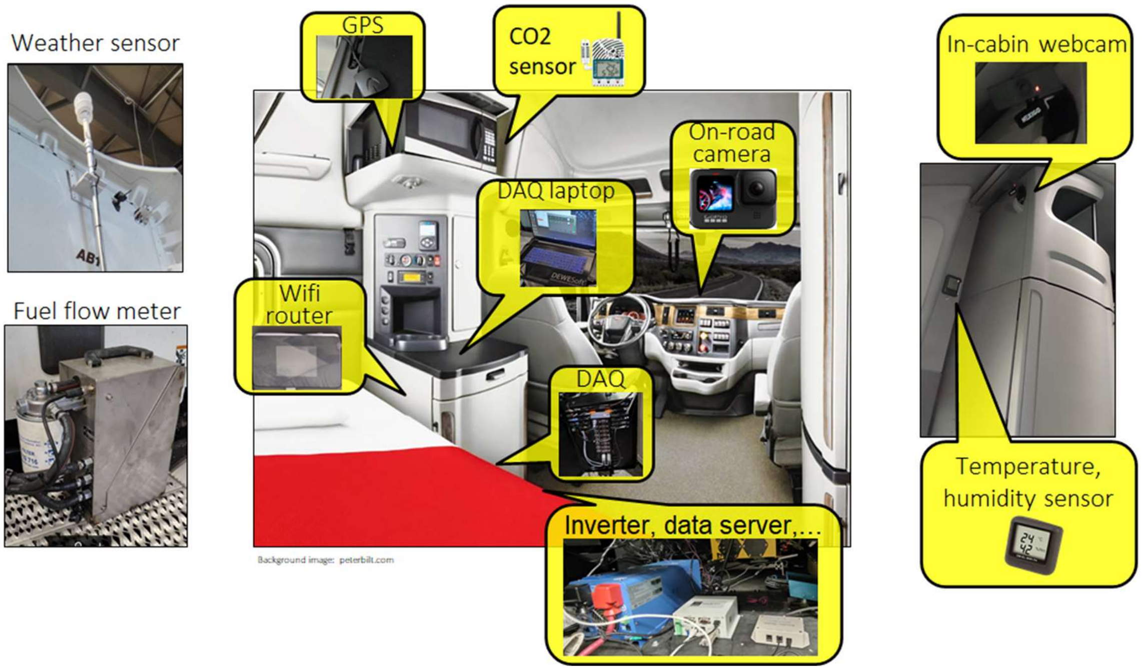
A list of measurements can be found in Table 7.

Table 7: List of measurements during on-road trials

Subsystem	Variable
Platooning performance and parameters	Radar
	Distance gap between two trucks
	Forward-looking video
	Truck-to-truck communication
	Vehicle telematic modules (BSM, LTE-V on-board unit)
	Lane deviation
Fuel consumption and emissions	Fuel mass flow rate, follower truck
	Fuel mass flow rate, lead truck
	Nitrogen oxides (NOx) emissions pre- and post- SCR (conditioned to availability on SAE J1939)
	Carbon dioxide (CO2) emissions
GPS	Position, speed, road slope from GPS

	Speed
	Road slope
Vehicle	Acceleration
	Braking
	Truck and trailer weight
	Instantaneous fuel consumption
	All SAE J1939 variables from truck, engine, transmission, and exhaust aftertreatment system
Vehicle cabin	HVAC parameters of temperature, barometric pressure, relative humidity, and CO2 concentration
	Driver face video for emotional identification; Eyeball tracking
	Steering wheel and cabin video
Vehicle dynamics	Wheels rotational speed
	Yaw angle and speed
	Steering wheel
	Roll angle and speed
Weather	Weather parameters including temperature, wind speed and direction, relative humidity, precipitation
Traffic	Traffic volume and neighboring traffic conditions
Driver	Driver data

Figure 10 shows the actual images of the equipment installed on trucks to collect data for platooning trials. It should be noted the weather station was only installed in the lead truck, and the CO2 sensor and Temperature and Humidity (T&H) sensors were only installed in the follower truck.



Background image: peterbilt.com

Figure 10: Equipment installed on the trucks for data collection

As shown in Figure 11, we collected a total of 339 parameters (see Appendix C) with up to 10 Hz sampling frequency from two trucks through the integrated DAQ system. One of the major focus areas of data sources for this project is the vehicle driving data via Controller Area Network (CAN) bus. Specifically, the SAE J1939 and CTPS-CAN (from Pronto) are used in both Class-8 trucks to collect data, which can aid in the assessment of vehicle fuel consumption and operation details during the trials.

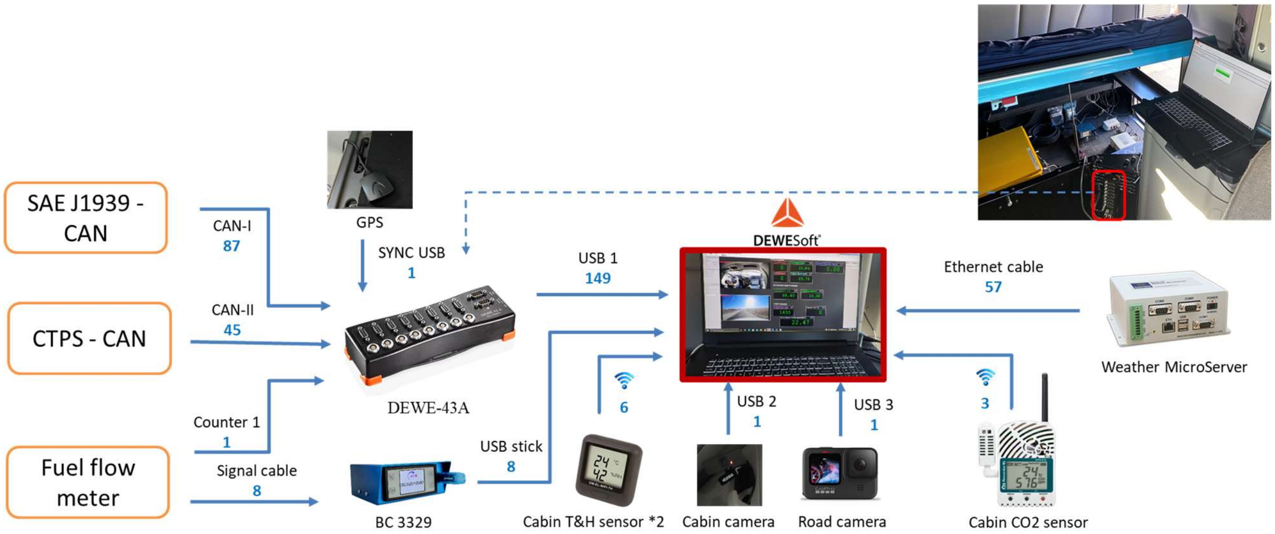


Figure 11: Overview of the integrated data acquisition (DAQ) system

Data Synchronization between Two Trucks

For this project, we used the DeweSoft data acquisition software, DewesoftX. We have also deployed hardware from DeweSoft, namely two DAQ's called the "Dewe-43A's", two "Dewe-GPS's", and two laptops in two trucks, separately. All the data sources were read into the DewesoftX software and stored synchronously. The data acquisition was synchronized on both trucks at a rate of 10Hz. This synchronization was accomplished by using GPS units for time synchronization and Dewesoft's proprietary DewesoftNet software, as shown in Figure 12.

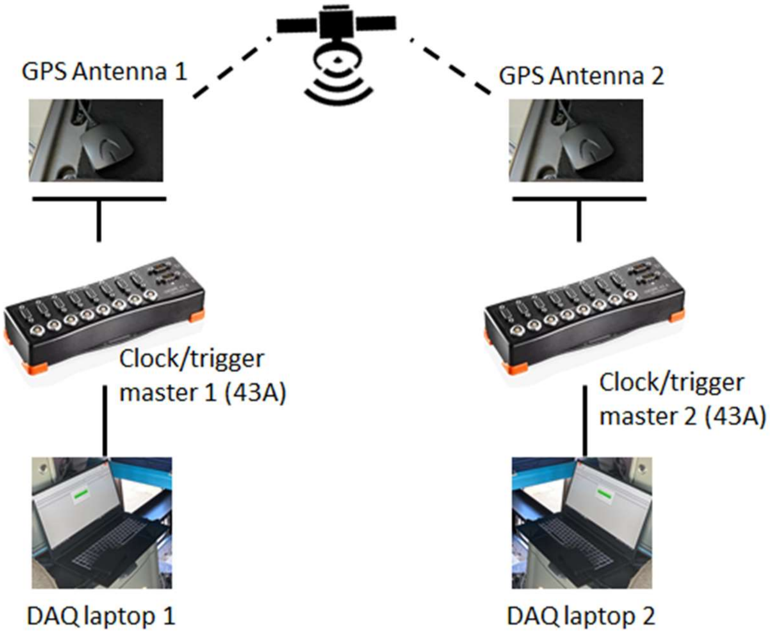


Figure 12: Data synchronization between two trucks

Fuel Flow Meter

Instantaneous fuel flow was measured using the AIC7004 flow sensor. The sensor measures the volumetric flow rate using the positive displacement principle. The fuel flow meter measured the fuel temperature at the measurement location, so conversion to mass flow rate is accurate. The sensor includes a heat exchanger for cooling the fuel to avoid overheating. The flow meter used a rotary piston technology that fits the fuel consumption measuring principle. A single moving piston oscillates softly in a measuring chamber protected by a thin layer of fuel, maintaining the piston self-floating. This allows the meter to have less mechanical friction, thus reduced wear. Under normal working conditions, the line pressure loss ahead of the measuring cell is of maximum 100 mbar. With the direct measurement principle, the installation of only one AIC Fuel Flowmeter was required. The fresh and cool fuel consumed is aspirated from the tank and its volume measured by the AIC fuel flowmeter. With this solution, no fuel is returning to the tank, and the fuel passing through the AIC volumetric measuring chamber precisely represents the actual engine fuel consumption. Specifications of the AIC flow meter are listed in Table 8.

Table 8: AIC 7004 NEMO flow meter specifications

Engine Power Rating	Up to 515 kW / 700 hp
Accuracy	Better than ±1% of reading
Fuel Consumption Flow Range	1 to 120 liter/hour
Repeatability	± 0.2 %
Resolution – pulses per liter	2000
Signal	NPN open collector; square 0.7 ms pulse width
Dimensions	390 x 135 x 310 mm / 15.4 x 5.3 x 12.2' (incl. filter)
Weight	13.8 kg (incl. filter)
Materials Flow Meter – Sensor	Brass, aluminum
O – rings	Viton™
Connectors	Chrome Steel M 16x1.5
Casing	Stainless steel
Admissible Pressure	-1 to 6 bars
Mounting Position	Vertical
Operating Temperature	-30°C to 90°C
Supply voltage through BC 3329	24 VDC

Figure 13 shows a picture of the AIC flow meter unit. The details for the installation of the fuel flow meter for the Cummins X15 engine is provided in Appendix D.

Figure 13: AIC positive displacement volume flow meter

The trials occurred in January during the winter season in Alberta, where the minimum temperature could be easily lower than -25 °C. In such conditions, the fuel in the rubber hoses would be frozen. Therefore, to prevent this happening, the fuel hoses need insulating against the clod. Figure 14 shows the insulation of hoses between the fuel flow meter and the engine.

Figure 14: Insulation of hoses between the fuel flow meter and the engine

The Fuel Flow Meter (FFM) transmits a TTL signal that gets interpreted by the BC3329 into fuel consumption data. The FFM functions by sending 2000 pulses for every litre of fuel that is consumed. This rating of 2000 ppl means that the FFM sends one pulse for every 0.5 ml of fuel consumed, regardless of the time it takes to consume that much fuel. Knowing this we can use the frequency of the pulses from the FFM to read the consumption signal. The FFM also transmits temperature data which will be used to determine the density of the fuel.

Weather Station

This project used a weather station from Columbia Weather Systems to record data about the current weather conditions. This data includes temperature, wind speed, wind direction, and more available measurements, as shown in Table 9.

Table 9: Sensor specifications of the weather station

Measurable Data	Range	Accuracy	Resolution
Wind Speed	0 to 60 m/s	±3% 0.01 m/s to 40 m/s, ±5% above 40 m/s and up to 60 m/s	0.01 m/s
Wind Direction	0-359°	±3° 0.01 m/s to 40 m/s, ±5° above 40 m/s and up to 60 m/s	1°
Temperature	-40 to +70℃	±3℃ @ 20℃	0.1℃
Relative Humidity	0-100%	±2% @ 20℃ (10%-90% RH)	1%
Barometric Pressure	300-1100 hPa	±0.5 hPa @ 25℃	0.1 hPa
GPS	-	Longitude and latitude report to 6 decimal places	<2.5 m

Figure 15 shows the hardware setup used for the weather station.

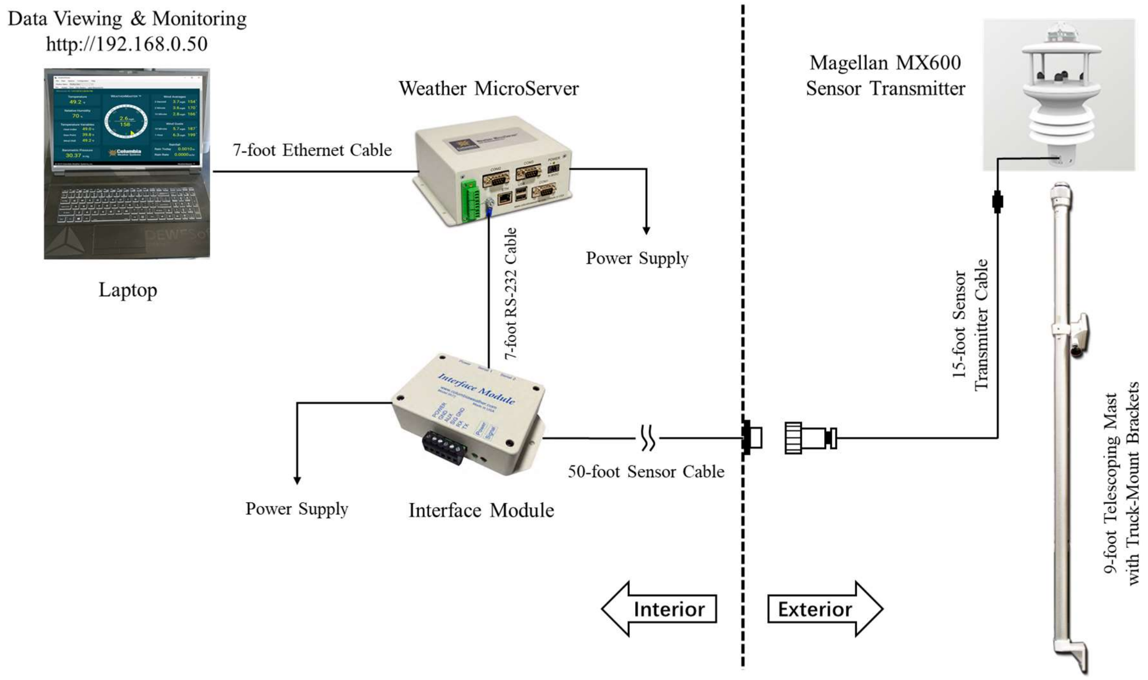


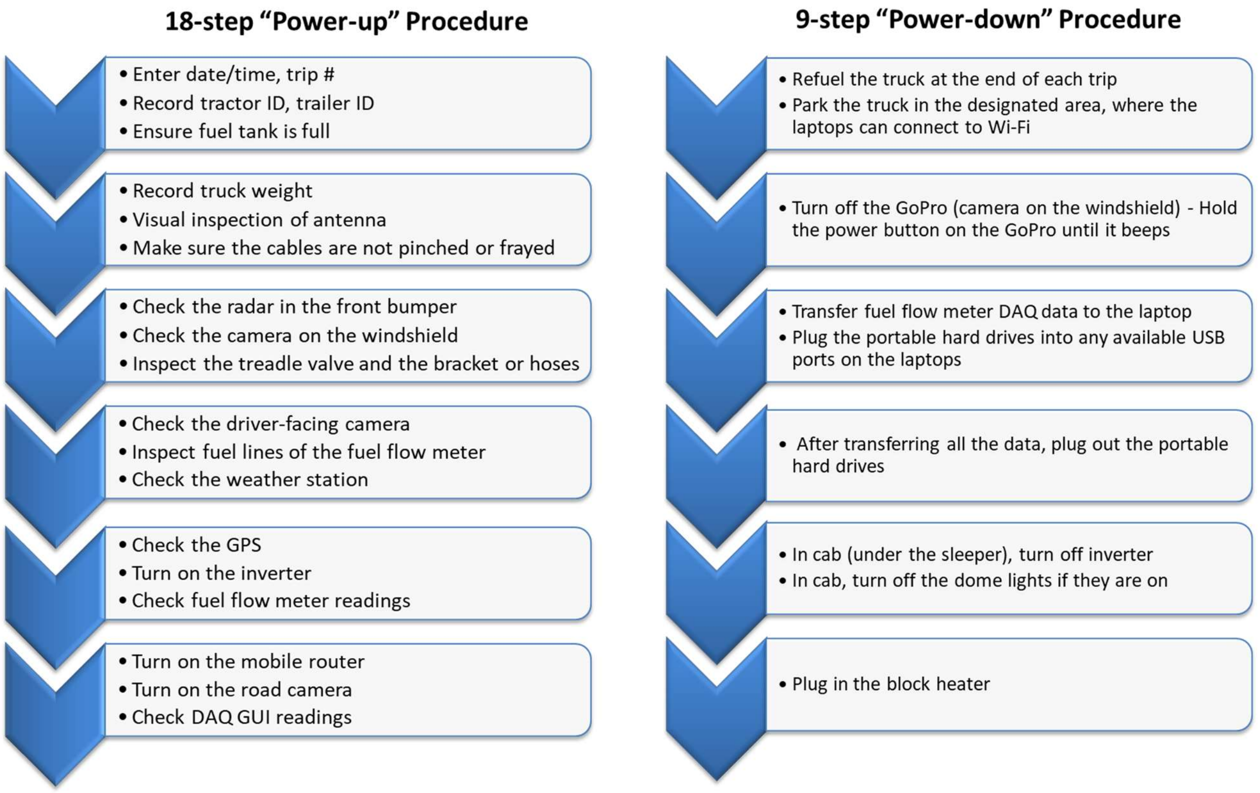
Figure 15: Hardware setup for the weather station

Figure 16 shows the mounted weather station on the truck of AB1, which was installed on top middle of the lead truck. The distance between the sensor of the weather station and the roof of the truck was 0.30 m.

Figure 16: Vehicle-mount weather station

4.2. Data Collection Process

There existed a great variety of equipment in this project. Proper and reasonable power-up / power-down procedures were needed to make sure all the sensors and devices work properly before commencing each trip. This enabled the research teams to collect data successfully upon completing each trip. Figure 17 represents the power-up and power-down procedures, which were created by the research team. There were 18 steps to power up all the systems before starting the trips, and 9 steps to power down all the systems after finishing the trips.



18-step "Power-up" Procedure

- Enter date/time, trip #
- Record tractor ID, trailer ID
- Ensure fuel tank is full
- Record truck weight
- Visual inspection of antenna
- Make sure the cables are not pinched or frayed
- Check the radar in the front bumper
- Check the camera on the windshield
- Inspect the treadle valve and the bracket or hoses
- Check the driver-facing camera
- Inspect fuel lines of the fuel flow meter
- Check the weather station
- Check the GPS
- Turn on the inverter
- Check fuel flow meter readings
- Turn on the mobile router
- Turn on the road camera
- Check DAQ GUI readings

9-step "Power-down" Procedure

- Refuel the truck at the end of each trip
- Park the truck in the designated area, where the laptops can connect to Wi-Fi
- Turn off the GoPro (camera on the windshield) - Hold the power button on the GoPro until it beeps
- Transfer fuel flow meter DAQ data to the laptop
- Plug the portable hard drives into any available USB ports on the laptops
- After transferring all the data, plug out the portable hard drives
- In cab (under the sleeper), turn off inverter
- In cab, turn off the dome lights if they are on
- Plug in the block heater

Figure 17: Power-up and power-down procedures

Remote Monitoring

By installing a mobile router in the truck, the research team members could monitor the on-road trials remotely and in real time. The ZTE Unite IV (device) was chosen as the mobile router, and its key technical specifications is shown in Table 10. Furthermore, the research team chose Bell as the wireless carrier for stable network connection when trucks were traveling on Highway 2.

Table 10: Key technical specifications of the mobile router

Operating system	Linux 4.9.160
CPU	Qualcomm SDX24
Network	LTE
Maximum download speed	Up to 800 Mbps
Mobile Wi-Fi hotspot	Support
Battery	3000 mAh
Standby time	Up to 12 days

SIM card	Nano SIM

As shown in Figure 18, all the data was collected on the laptop, which was located in the cabin of the truck. The cabin CO2 sensor could transfer the data to the laptop through connected USB cable. Meanwhile, the device itself could also upload the data to the cloud via Wi-Fi, where we could download the data anytime and anywhere. The cabin temperature and humidity (T&H) sensor needs the Wi-Fi to transfer the data to the laptop, but it could store the data temporally in the device in case it could not connect to the mobile router. The research team members could access the laptop and remotely control it by logging in the TeamViewer account, which also allowed us to transfer data wirelessly.

Figure 18: Data transferring and Remote Monitoring via Wi-Fi

Furthermore, we also monitored the real-time data of the on-road trials via mobile phones, which allow us to monitor the trials anytime and anywhere through the Internet. Figure 19 shows the graphical user interface (GUI) of the DAQ system, which allowed us to visually see the real-time data during the trips. Furthermore, it also assisted the research team members in validating data quality and then coordinate with drivers if needed.


Lead Truck

Current time 10:29:40.499
Cabin Camera
Road Camera
CTPS
PlatoonEngaged 0
Lead Speed (km/h) ACT 89.82
Calculated Seperation Gap (s) ACT 0.00
CopilotEngaged 1
Follower Speed (km/h) ACT 89.78
AIC Fuel Flow
1HzConsumption (L/h) ACT 45.00
TotalConsumption (L) ACT 43.54
J1939
Engine Speed (rpm) ACT 1041
Percent Load (%) ACT 66
Wheel Based Vehicle Speed (km/h) ACT 89.97

Follower Truck

Cabin Camera
Road Camera
CTPS
PlatoonEngaged 0
Lead Speed (km/h) ACT 89.28
TimeGap (s) ACT 3.0
Calculated Seper 6.94
CopilotEngaged 1
Follower Speed (km/h) ACT 87.41
CruiseCtrlSwitch 0
TransmissionCur 11
AIC Fuel Flow
1HzConsumption (L/h) ACT 43.20
TotalConsumption (L) ACT 37.56
J1939
Engine Speed (rpm) ACT 1013
Percent Load (%) ACT 83
Wheel Based Vehicle Speed (km/h) ACT 87.75

Figure 19: Graphical user interface (GUI) of the DAQ system during real time monitoring of truck operation

4.3. Collected Data Overview

In this project, a total of more than 10 data sources were installed in both trucks. In AB1, we collected the data from weather station, fuel flow meter, CAN bus (SAE J1939 & CTPS), videos (road & cabin). In AB2, we collected the data from fuel flow meter, CAN bus (SAE J1939 & CTPS), videos (road & cabin), cabin CO2 sensor and cabin T&H sensors. As shown in Figure 20, all the data could be transferred to a portable hard drive or the TeamViewer (wirelessly), and then was uploaded to the corresponding Google Drive folders by the research team members.

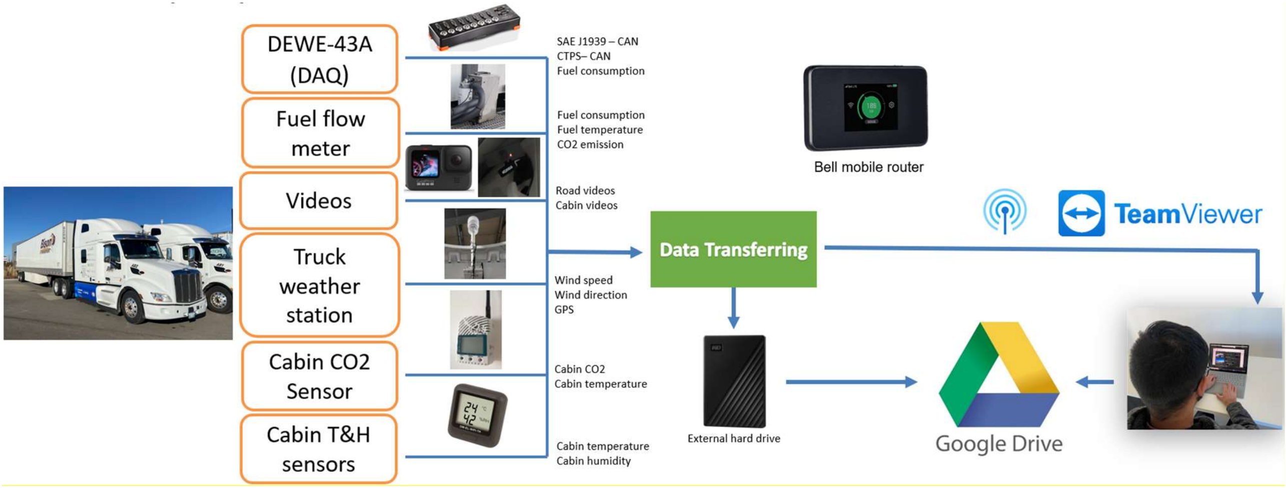
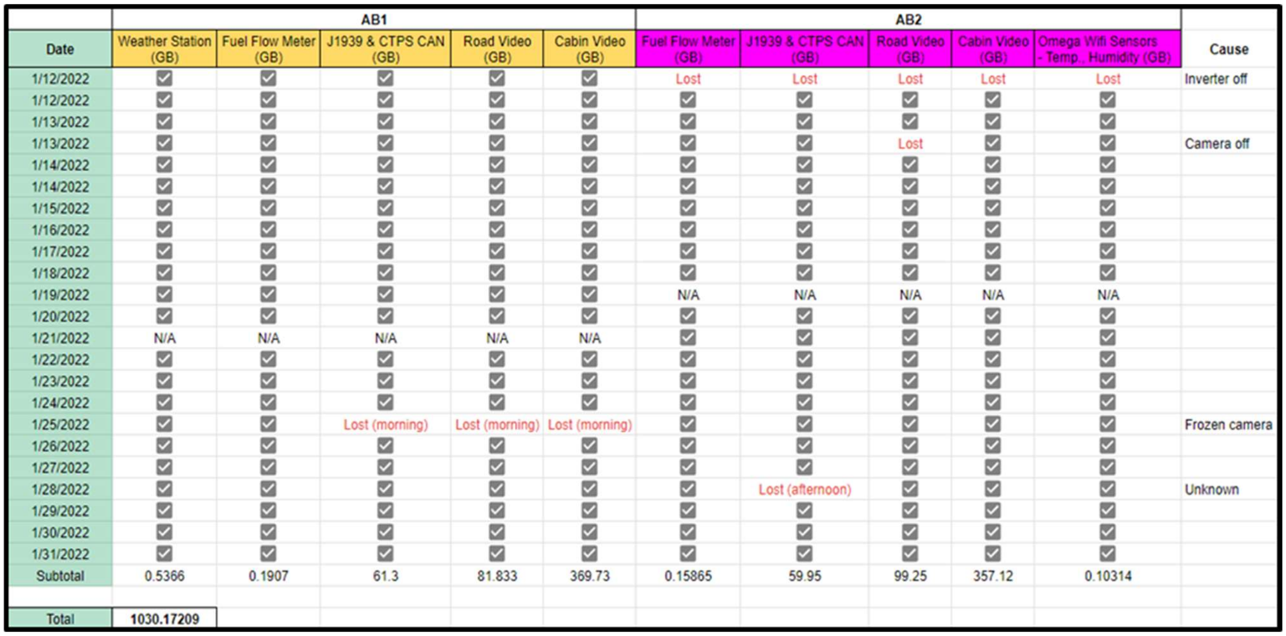


Figure 20: Data collecting and transferring

Table 11 shows the actual collected data. The research team collected a total of 1,030 GB data. For each round-trip, up to 67.9 GB data was collected with the videos accounting for the largest portion, reaching 89.7%.

Overall, we collected 96.4% of the planned data. The data loss problems in the trials were caused by the drivers or the equipment limitations as noted in Table 11. For example, on the Jan 12 trip the driver forgot to turn on the inverter or during the Jan 25 trip, the screen of GoPro road camera in the truck got frozen and affected data recording by the ICEDAQ system.

Table 11: Summary of the actual collected data and breakdown of the data size



	AB1					AB2					
Date	Weather Station (GB)	Fuel Flow Meter (GB)	J1939 & CTPS CAN (GB)	Road Video (GB)	Cabin Video (GB)	Fuel Flow Meter (GB)	J1939 & CTPS CAN (GB)	Road Video (GB)	Cabin Video (GB)	Omega Wifi Sensors - Temp., Humidity (GB)	Cause
1/12/2022	☑	☑	☑	☑	☑	Lost	Lost	Lost	Lost	Lost	Inverter off
1/12/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/13/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/13/2022	☑	☑	☑	☑	☑	☑	☑	Lost	☑	☑	Camera off
1/14/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/14/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/15/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/16/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/17/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/18/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/19/2022	☑	☑	☑	☑	☑	N/A	N/A	N/A	N/A	N/A	
1/20/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/21/2022	N/A	N/A	N/A	N/A	N/A	☑	☑	☑	☑	☑	
1/22/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/23/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/24/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/25/2022	☑	☑	Lost (morning)	Lost (morning)	Lost (morning)	☑	☑	☑	☑	☑	Frozen camera
1/26/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/27/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/28/2022	☑	☑	☑	☑	☑	☑	Lost (afternoon)	☑	☑	☑	Unknown
1/29/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/30/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
1/31/2022	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
Subtotal	0.5366	0.1907	61.3	81.833	369.73	0.15865	59.95	99.25	357.12	0.10314	
Total	1030.17209										

Figure 21 shows the types of the collected data. Dewe-43A collected the SAE J1939, CTPS CAN data, fuel flow data, and generated .dxd files. Fuel flow meter data acquisition system (BC 3329) collected the fuel consumption, fuel temperature, and generated .csv files. The road videos and cabin videos (.avi files) were recorded in Dewe-43A. The weather station collected wind speed, wind direction, GPS, cabin temperature and cabin humidity, and generated .txt files. Cabin CO2, and cabin temperature (.trz files) were collected by the CO2 sensor. After collecting all kinds of files, we input the data into MATLAB, and generated the consolidated and synchronized data file in .xlsx and .mat formats.

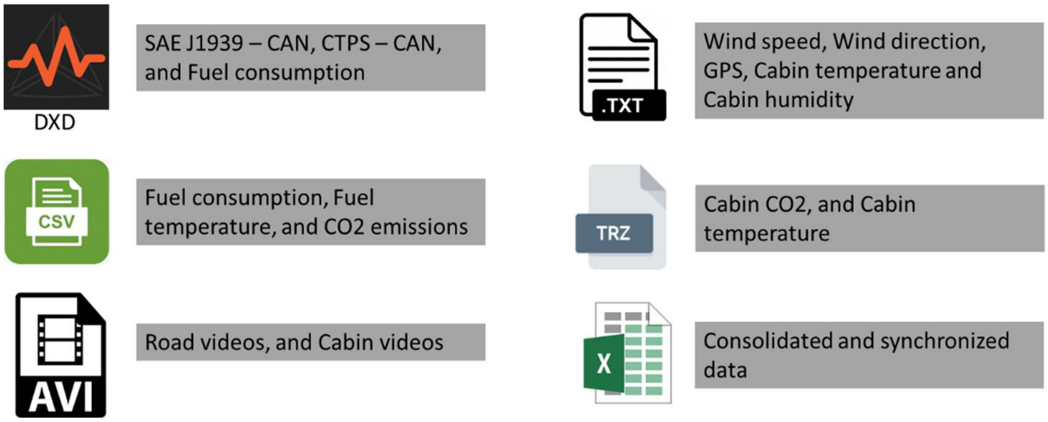


Figure 21: Metadata and types of collected data

Furthermore, the research team developed a depository to properly organize all the data, as shown in Figure 22. The data was organized into preliminary data and processed data.

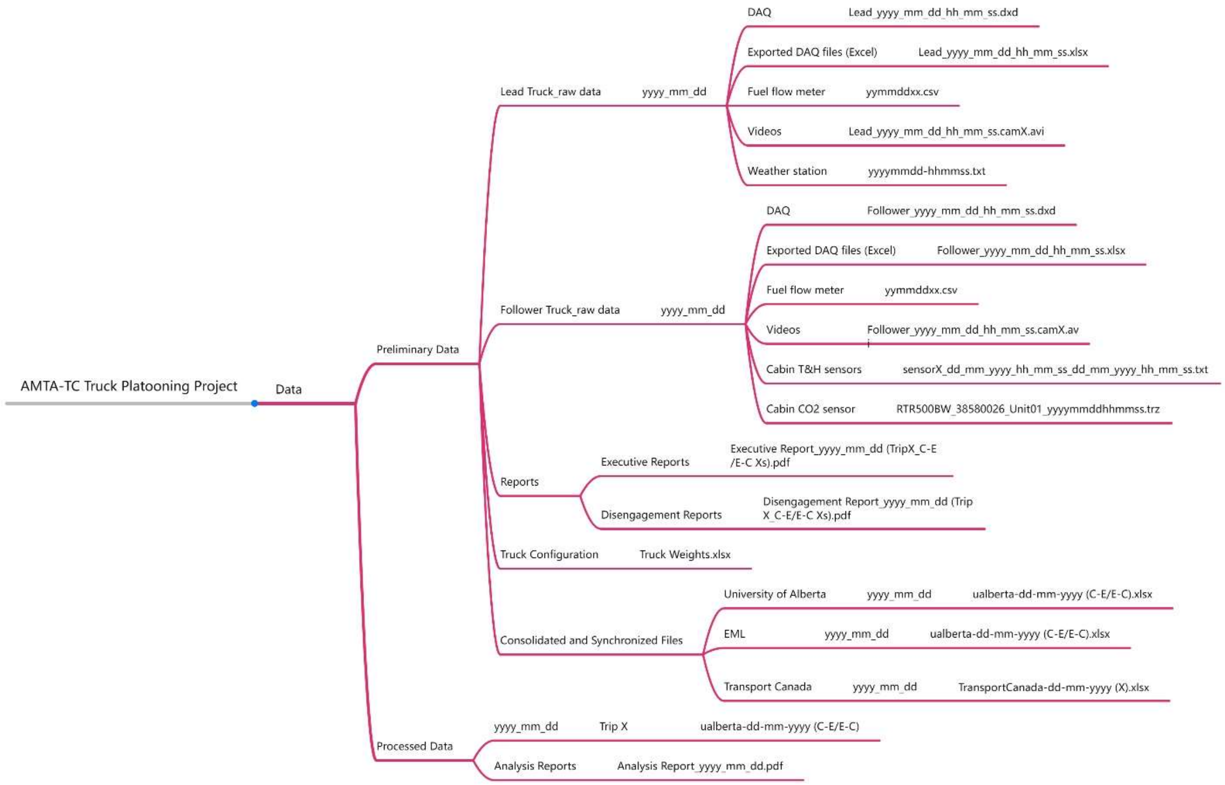


Figure 22: Structure of designed data depository

5. Test Conditions

Truck Weights

The maximum weight for a five-axle tractor/trailer combination is 39,500 kg in Canada. The total weights of the lead truck (AB1) and follower truck (AB2) are shown in Figure 23, in which the weights are sorted by the trips with different time gaps. In summary, the truck weights ranged from 15,963 to 39,342 kg for all trips. During the platooning trips, the truck weights ranged from 15,963 to 38,785 kg. AB1 was heavier than AB2 in 86% of platooning trips. Furthermore, in 31% of platooning trips, both trucks had a similar weight (±5%).

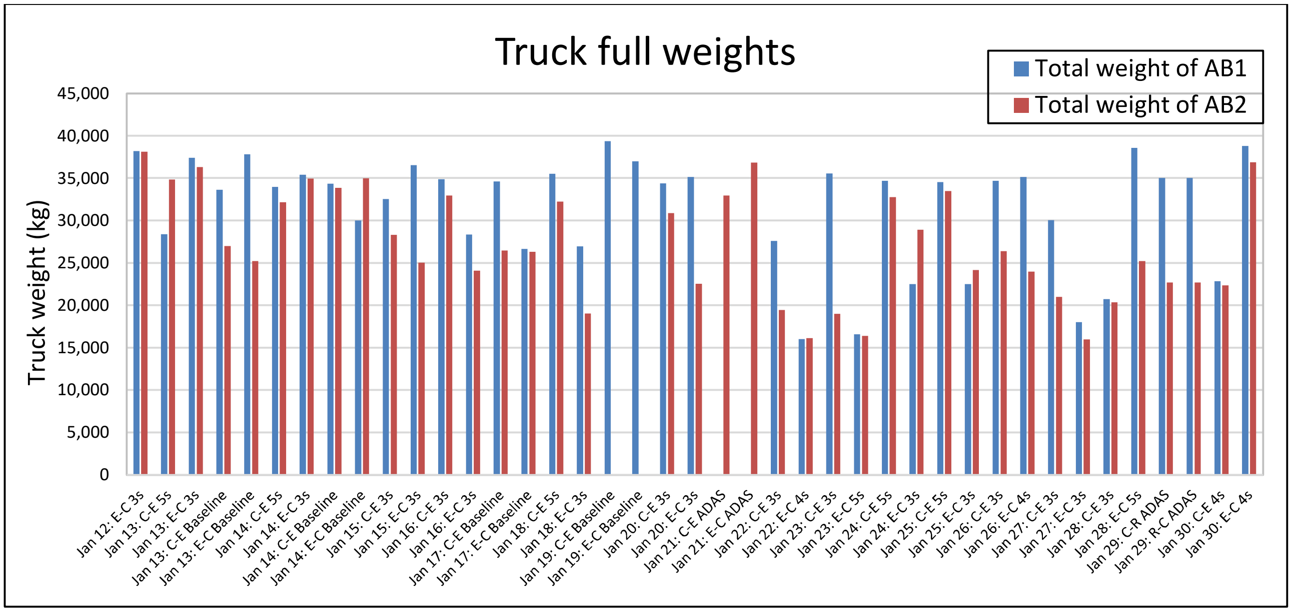


Figure 23: Truck full weights during trials

Ambient Temperatures

Ambient temperatures were collected by the weather station, which was installed on the lead truck (AB1). The trip on Jan 19, 2022 from Calgary to Edmonton was the coldest trip among all trips. Figure 24 shows the ambient temperature variation during the trip on Jan. 19, 2022. The minimum temperature was -26.5 °C, the maximum temperature was -16.1°C, and the average temperature was -20.9 °C.

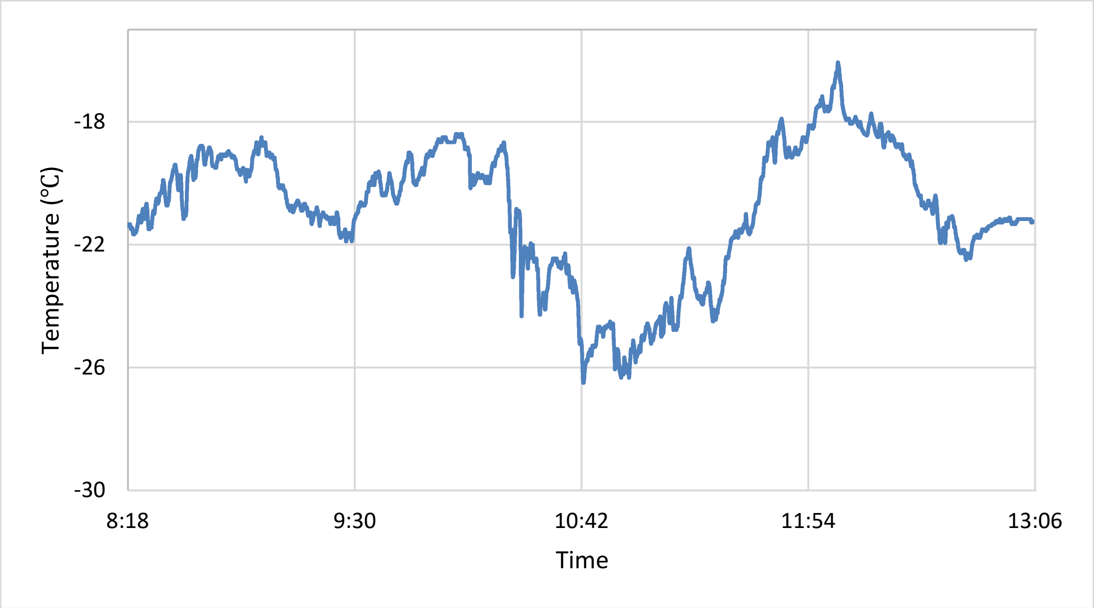
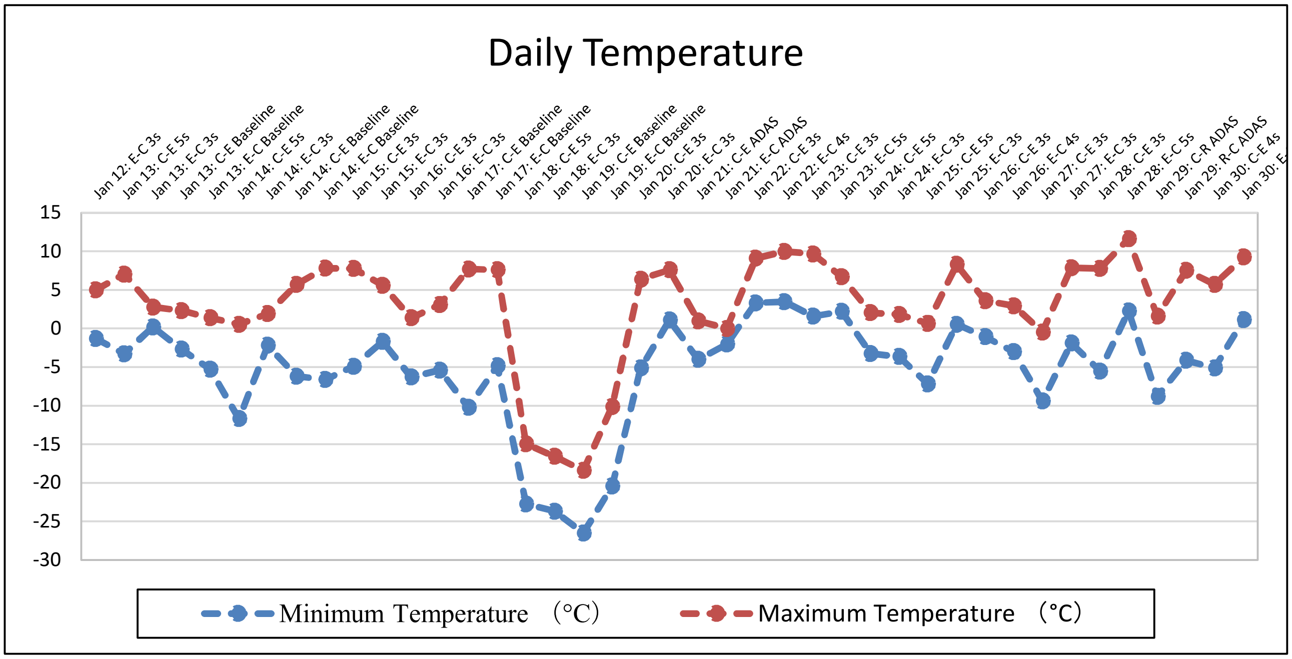


Figure 24: Ambient temperature variations on Jan19 for the Calgary to Edmonton trip

Furthermore, the minimum and maximum ambient temperatures for every trip are shown in Figure 25. We can see that the ambient temperatures ranged from 12 to -27 °C during the trials. In 78% of platooning trips, the minimum temperature was below 0 °C.



*The temperatures on Jan. 21 (AB1 was out of service) were taken from https://www.timeanddate.com/weather/canada/red-deer/historic?month=1&year=2022.

Figure 25: Ambient temperatures

Apparent Wind Speed under Platooning

The wind measurements were collected by the weather station, but we needed to calibrate the wind measurements against those from the stationary weather station to reduce the uncertainty in wind measurements. This is due to the fact that wind measurements on the truck are affected by the speed of the truck as well as the flow boundary layer around the truck cabin. For the detailed calibration processes, please see Appendix E.

The wind speed measurements by the mobile weather station on the top of the truck cabin is denoted as "apparent wind speed" which is the wind experienced by the truck in motion and is the relative velocity of the wind in relation to an observer in the truck. As shown in Figure 26, during all the platooning trials, the apparent wind speed ranged from 33.0 to 152.9 km/h. Furthermore, the maximum apparent wind speed difference in a trip was 95.4 km/h (Jan 26: C-E 3s), and the minimum apparent wind speed difference in a trip was 24.2 km/h (Jan 24: E-C 3s).

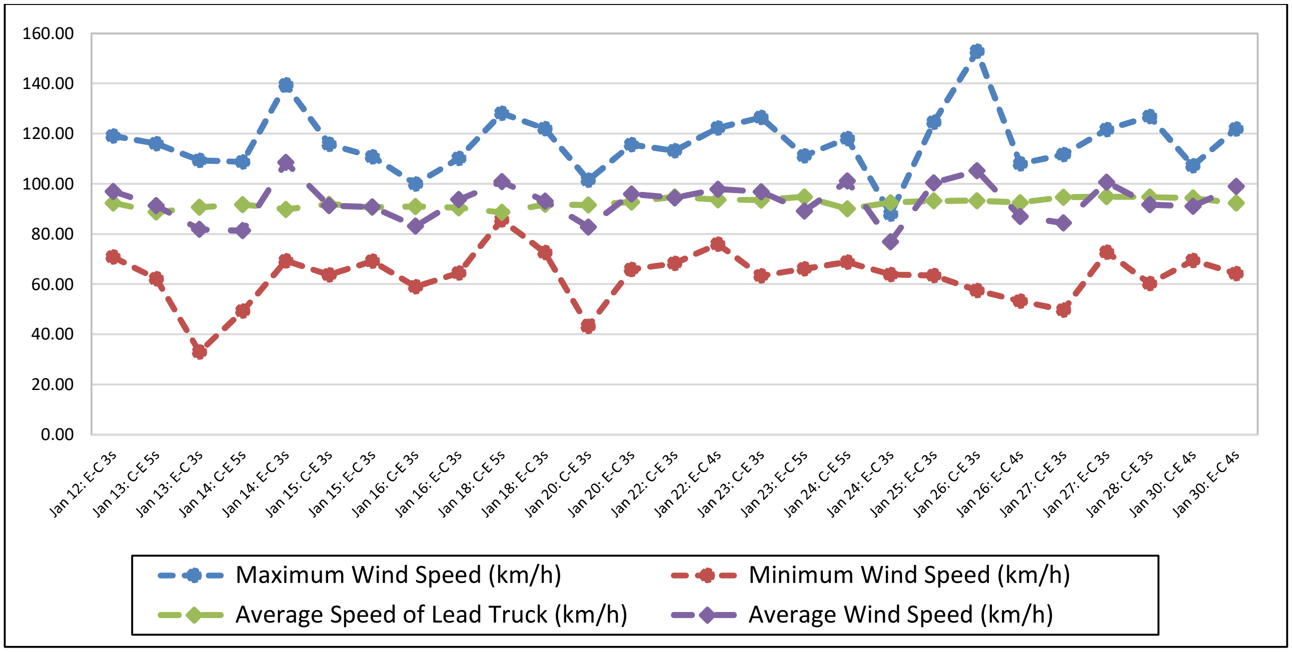
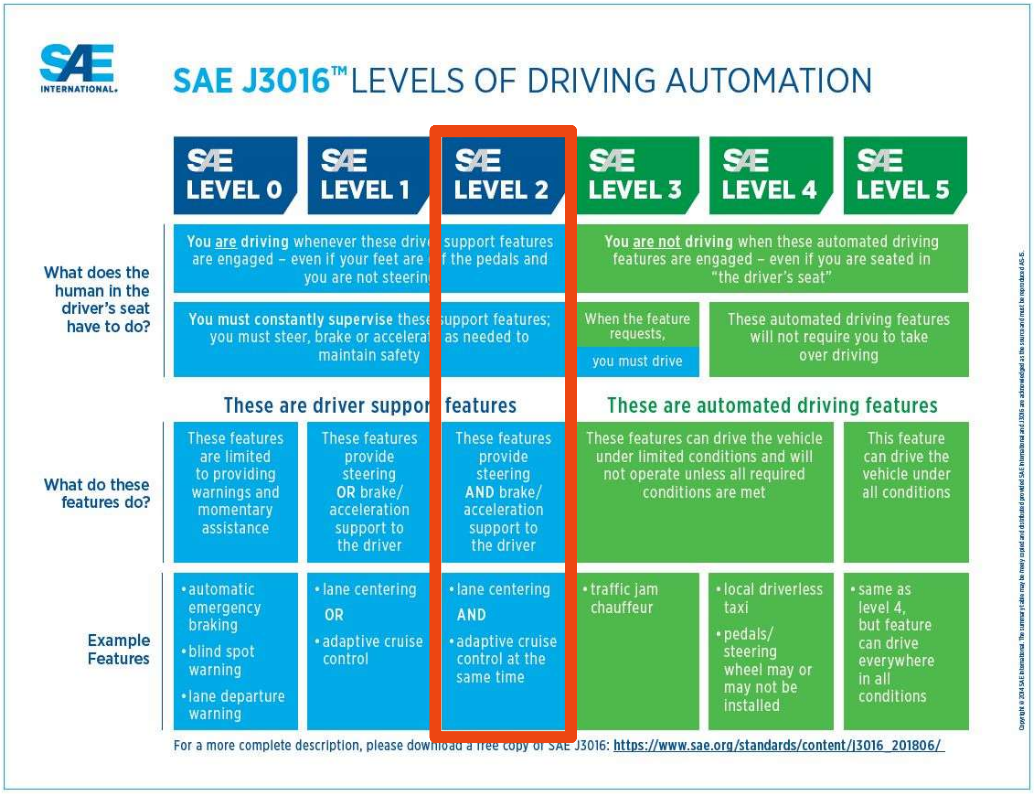


Figure 26: Apparent wind speeds during platooning trials

6. Platooning Performance

Platooning Operation/Background

The platooning system in this project is classified as SAE Level 2 automation according to SAE J3016 standard as shown in Figure 27, which means the system supports steering and deceleration/acceleration (e.g., lane centering and adaptive cruise control at the same time), but the driver must constantly monitor these support features and be ready to take over control of the truck as needed to maintain safety.



SAE INTERNATIONAL.

SAE J3016™ LEVELS OF DRIVING AUTOMATION

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	**You are driving** whenever these drive support features are engaged – even if your feet are f the pedals and you are not steerin			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerat as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver suppor features			These are automated driving features		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering OR brake/ acceleration support to the driver	These features provide steering AND brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering OR • adaptive cruise control	• lane centering AND • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/ steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

For a more complete description, please download a free copy of SAE J3016: https://www.sae.org/standards/content/J3016_201806/

Figure 27: Definition and functions of different levels of automated driving based on SAE J3016

To allow the two trucks to engage into a platoon, the following conditions must be met:

1. Both the follower truck and lead truck should be engaged in Copilot mode.
2. Both the follower truck and the lead truck should be in the same lane.
3. No other vehicles should be between the follower truck and lead truck.

Table 12 shows a summary of conditions that would affect the Copilot and CTPS platooning engagement status.

Table 12: CTPS platooning engagement rules

Condition	AB2 Copilot remains ON	Platoon Engagement
AB1 driver brakes	√	√
AB1 driver accelerates	√	√
AB1 cancels copilot	√	×
Apply torque by the AB1 driver to steering wheel for a certain time duration	√	×
Apply torque by the AB2 driver to	×	×

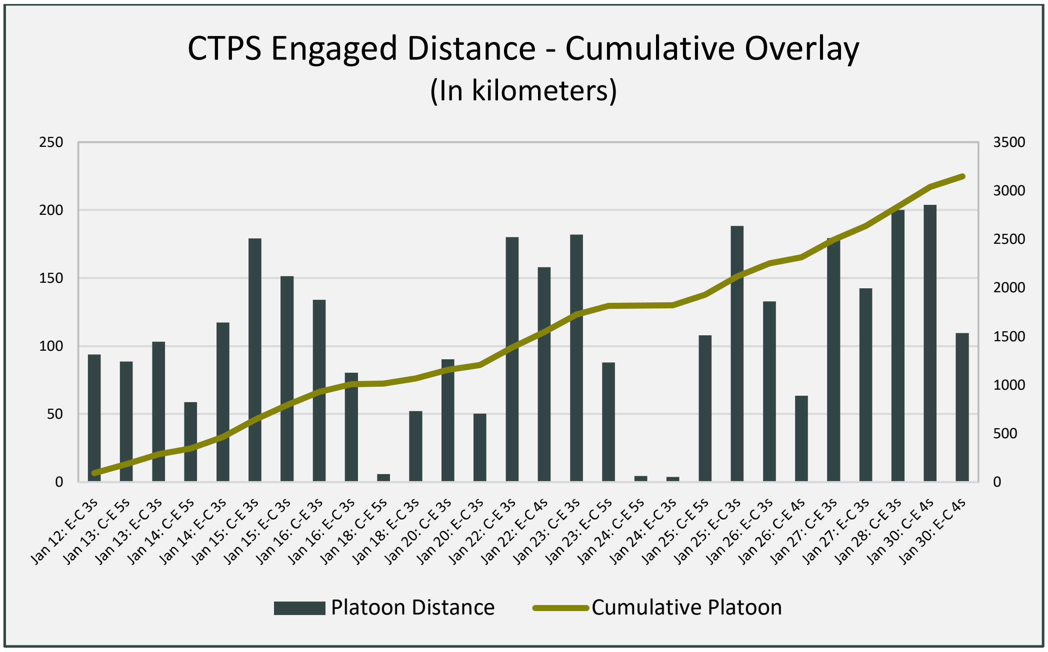
steering wheel for a certain time duration		
AB2 driver brakes hard	√	√
AB2 driver accelerates	√	√
Cut-in	√	×
Signal lost	√	×
Bad road conditions (e.g. faded lane markings, shadows, etc.)	×	×
Inclement weather conditions (e.g. blowing snow, slush, etc.)	×	×
Bad sensor conditions (e.g. radar/camera is obstructed, etc.)	×	×
AB2 cannot see AB1 on a curvy road	√	×

It is important to note the difference between the Copilot disengagement and Platoon disengagement. For Copilot disengagement, the driver performs an action to disengage but for Platoon disengagement, the system performs the disengagement.

Platooning Overview

There was a total of 41 trips completed during the CTPS trial, including a total traveling distance of 23,400 km. 28 of the trips were platooning trips, in which 3, 4 and 5 sec were set for the time gap between the two trucks. The total platooning mileage was 3,150 km, and the total platooning duration was 2,075 minutes, as shown in Figure 28. In some trips, the platooning mileage/duration was too small, such as Jan 18: C-E 5s, Jan 24: C-E 5s, and Jan 24: E-C 3s. These trips included the situations in which the driver was not comfortable with using the headband as part of the measurement device for the human factor study, weather/road conditions or heavier follower-truck.

(a) CTPS engagement distance



(b) CTPS engagement duration

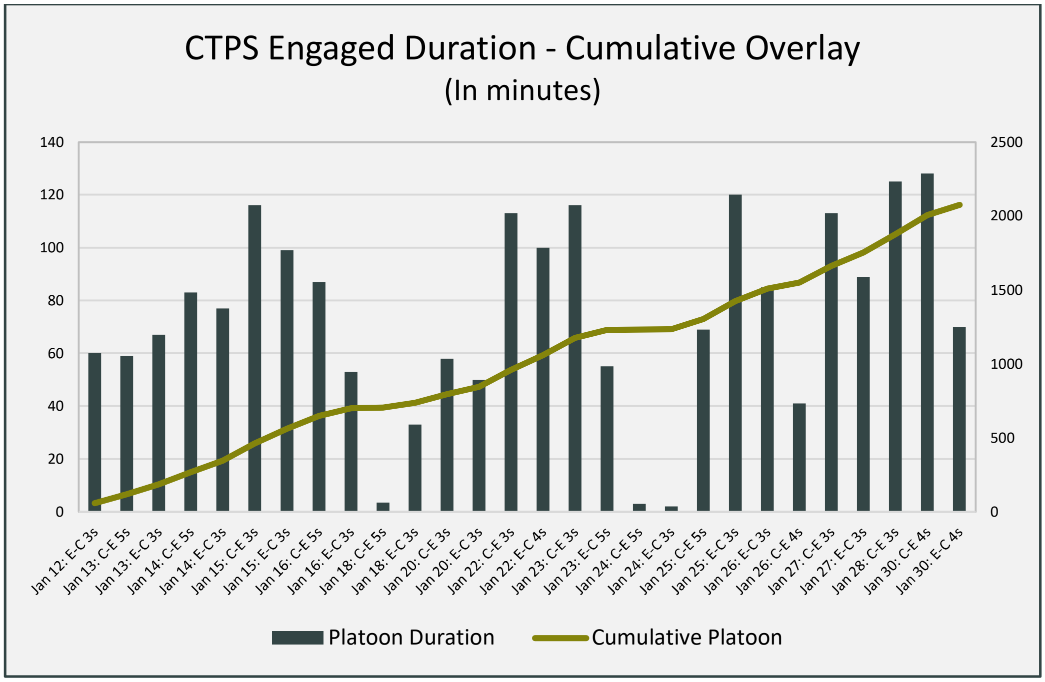


Figure 28: Distance and duration of platooning trips

Platoon Engagement Ratio under Different Road Surface Conditions

During the platooning trips, there were four road surface conditions, including bare dry, bare wet, partly covered snow, and shoulder ice/snow. The definition of different road surface conditions is available in Appendix B. The largest portion was bare dry, which accounted for 71.4% of the platooning trial. Furthermore, the partly covered snow and shoulder ice/snow road conditions only occurred in two platooning trips. The remaining trips were with bare wet road conditions (21%), as shown in Figure 29.

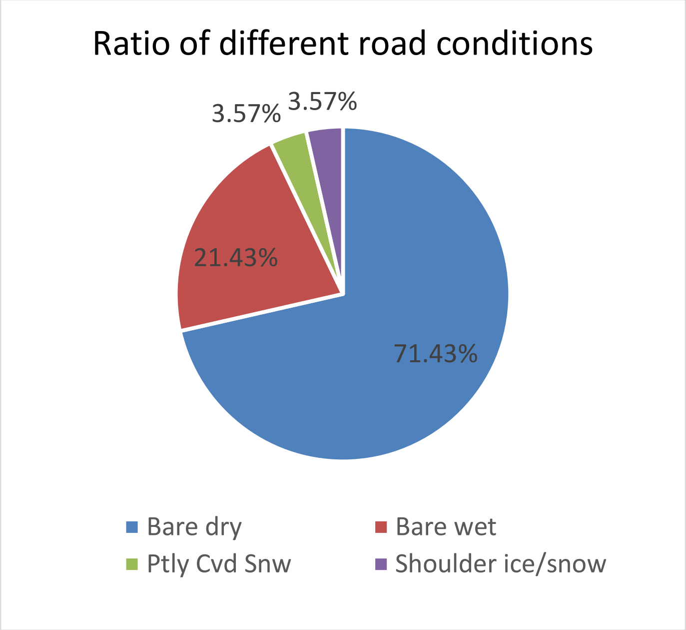


Figure 29: Road surface conditions during platooning trips

Furthermore, the research team calculated the platoon engagement ratio based on the platoon engagement "time" divided by the time it takes in each platooning to drive between Airdrie and Leduc (platooning portion of route). As shown in Figure 30, under the bare dry surface conditions, the platoon engagement ratio ranged from 4.0% to 88.9%, with the average ratio being 59.9%. Excluding two trips (Jan 24: C-E 5s & Jan 26: E-C 4s)[2], the platoon engagement ratio ranged from 36.3% to 88.9%, with the average ratio being 65.3%.

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[2] These two trips included the same driver who did not feel comfortable for wearing the Muse headband for a long period time for the human factor studies. This could have affected his use of the CTPS system during the trip.

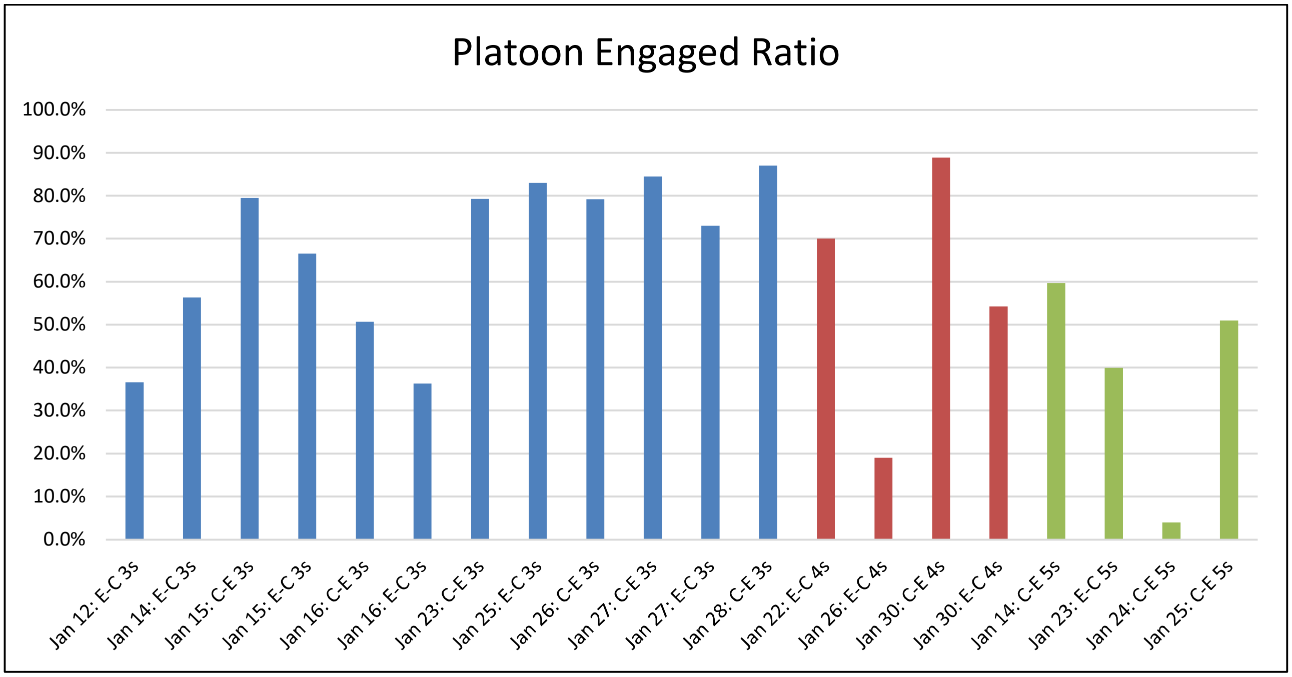


Figure 30: Platoon engagement ratio under bare dry road conditions

As shown in Figure 31, under the bare wet surface conditions, the platoon engagement ratio ranged from 40.7% to 96.0%, and the average ratio was 62.5%.

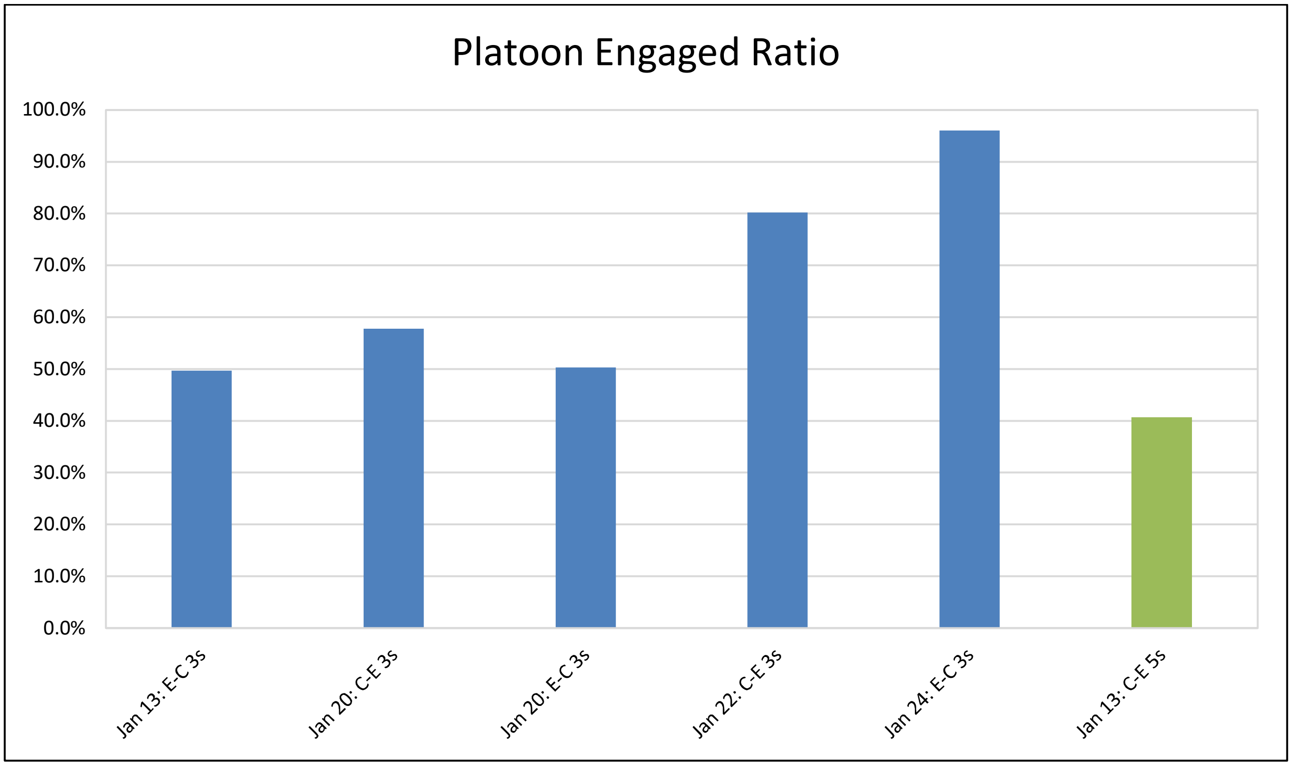


Figure 31: Platoon engagement ratio under bare wet road conditions

Furthermore, under the partly covered snow and shoulder ice/snow road conditions, the average platoon engagement ratios were 59.0% and 66.1%, respectively.

Time Gap

Time gap is the amount of time between the two trucks passing through a given point in a trip. The following formula was used to calculate the instantaneous time-gap:

$$h_f(t) = \frac{x_l(t) - x_f(t) - L}{v_f(t)} \qquad (1)$$

where h is the time gap, $v_f(t)$ denotes the vehicle speed of the follower truck, $x_l(t)$ and $x_f(t)$ represent the positions of lead and follower trucks at time t, respectively, and L is the length of the truck, i.e., tractor + trailer.

Figure 32 shows the actual time gaps under different set time gaps (e.g. 3, 4, and 5 sec). The trucks typically had an average speed of 95 km/h. At this speed, 1 sec gap is equal to 26.4 meters traveling distance. As seen in Figure 32, there is approximately 1 sec difference between the commanded and actual time gaps. Furthermore, considering the platooning safety, Pronto's CTPS system included a 10-meter buffer; thus, there will be a minimum of 10-meter gap between the lead and follower trucks in all conditions. This was additional to the commanded (set) time gap selected by the driver.

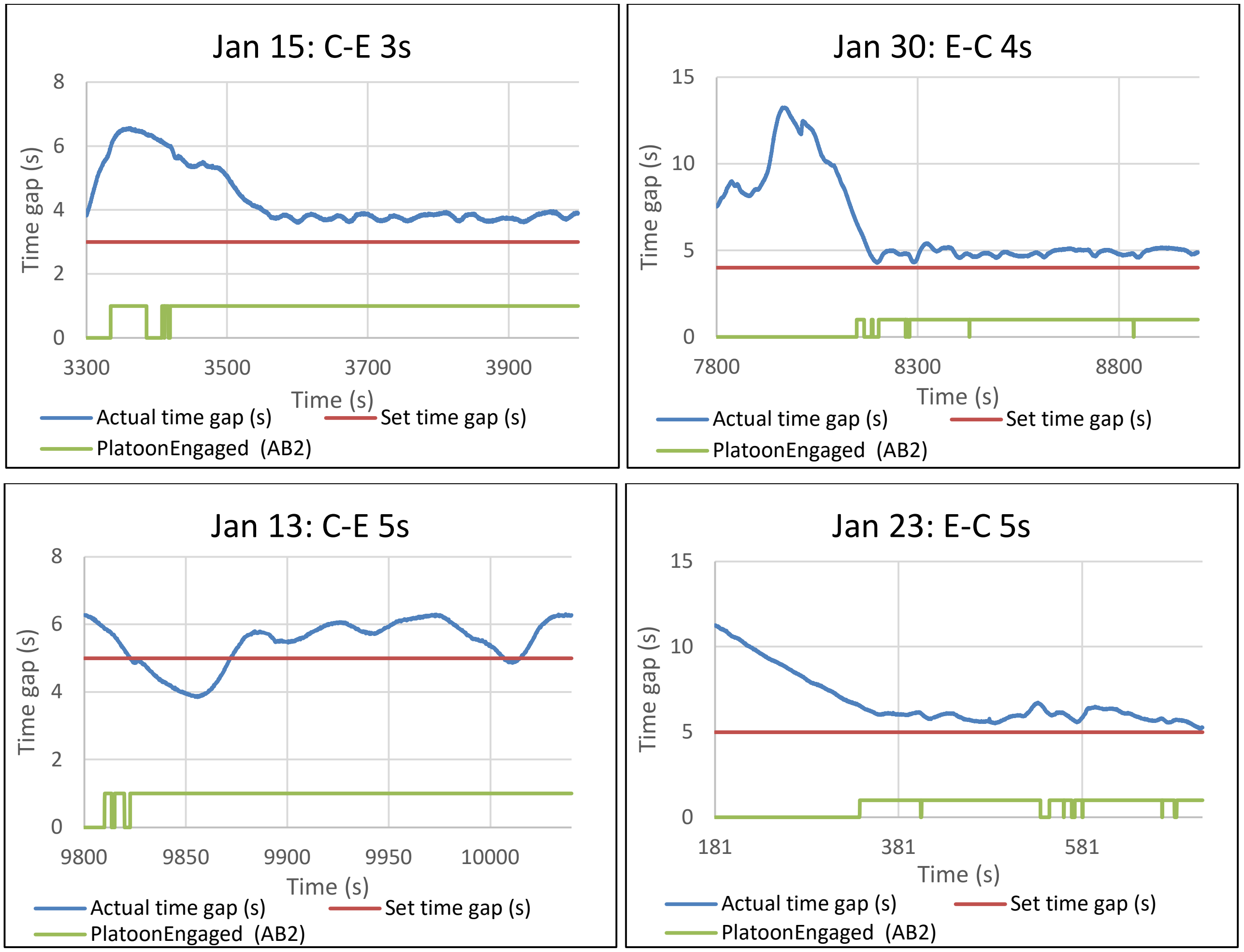


Figure 32: Actual vs requested time gaps

Figure 33 characterized the separation gap sequenced in series of 3-sec Edmonton-bound, 3-sec Calgary-bound, 4-sec Edmonton-bound, 4-sec Calgary-bound, 5-sec Edmonton-bound and 5-sec Calgary-bound. As shown in Figure 33, the standard deviation for time gap variations ranged from 0.61 to 1.84 sec for all the platooning trips. The trips with 3-sec commanded gap generally had higher time gap variations. The large variation for trip 26 in the figure was due to too short platooning duration (< 3 min).

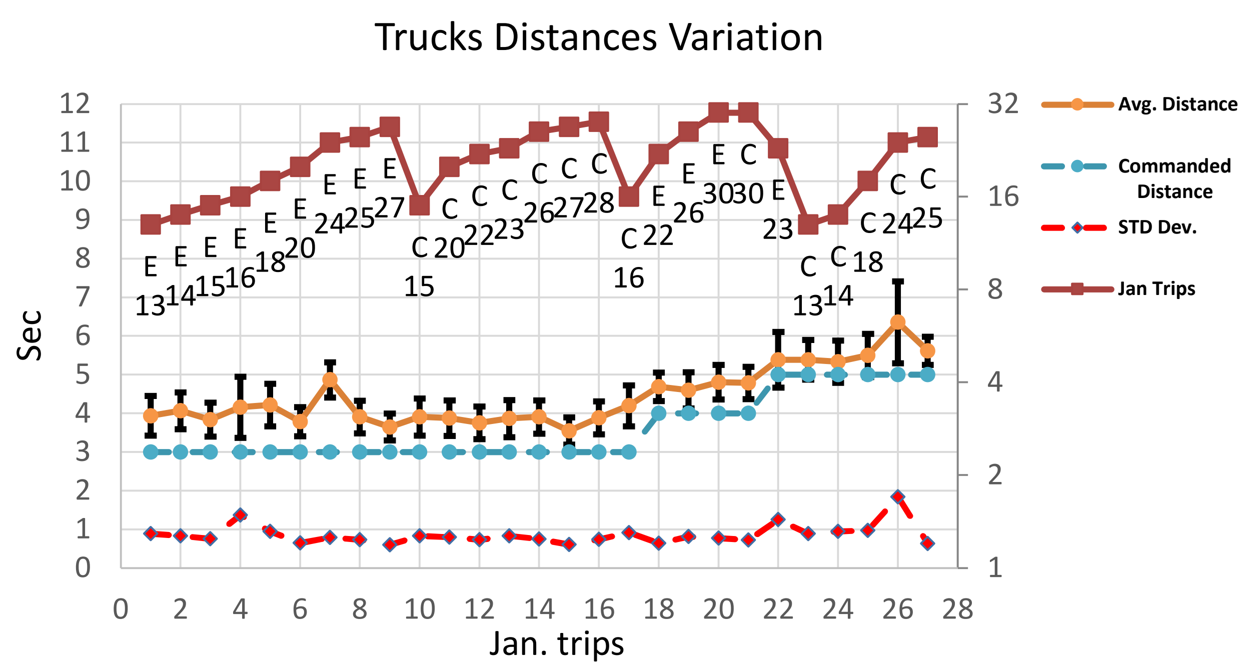


Figure 33: Time gap variations during platooning trips. The bars on Avg. Distance graph show confidence interval with 95% significance.

The effect of time gaps on the quantity of platoon disengagement is shown in Figure 34. When the time gap was set to 3 s, the maximum number of disengagements was 106, the minimum number of disengagements was 3, and the average disengagement number was 60. However, when the time gap was set to 5 s, the maximum disengagement number was 131, the minimum disengagement number was 7, and the average disengagement number was 81. This could be due to the fact that larger platooning distance led to more cut-ins by traffic vehicles, as reported in the analysis done by the traffic interaction team.

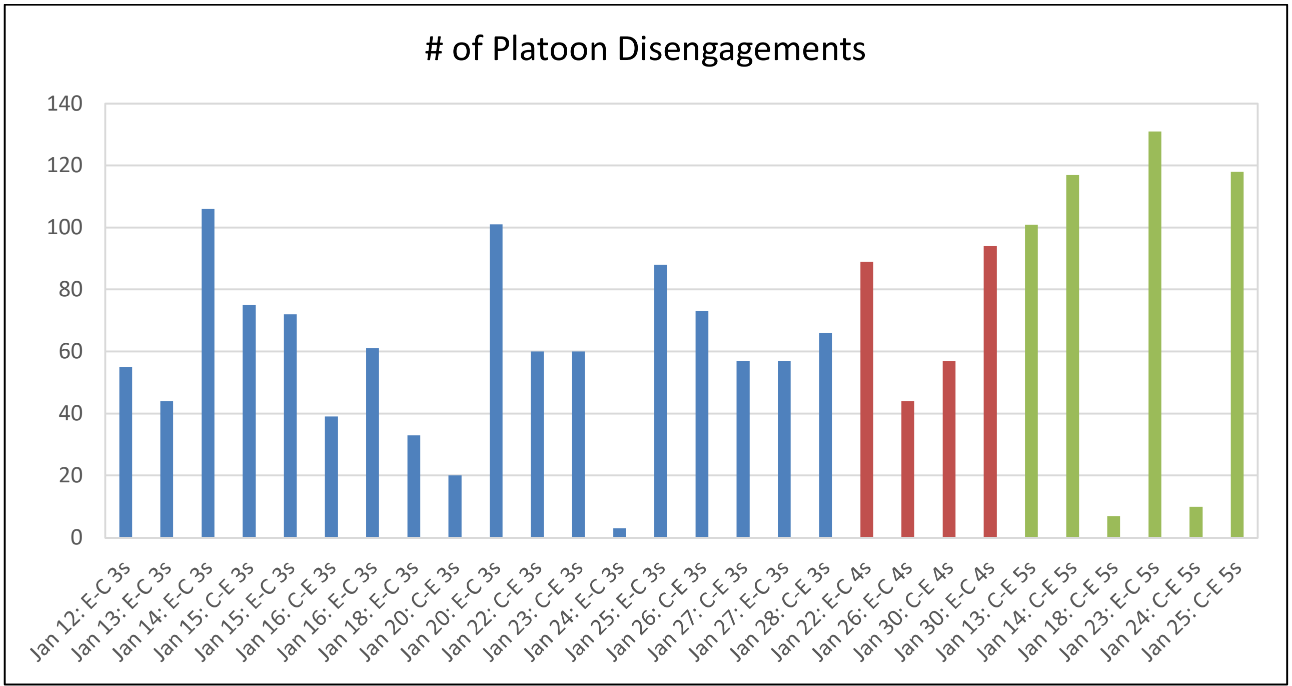


Figure 34: Number of platoon disengagements

Truck Speed under Platooning

The average speed of the follower truck under platooning ranged from 87.8 to 95.2 km/h (Figure 35). Furthermore, the maximum speed ranged from 96.1 to 114.5 km/h, and the minimum speed ranged from 62.6 to 80.9 km/h. The truck lower speed values were mostly affected by the traffic conditions on the road.

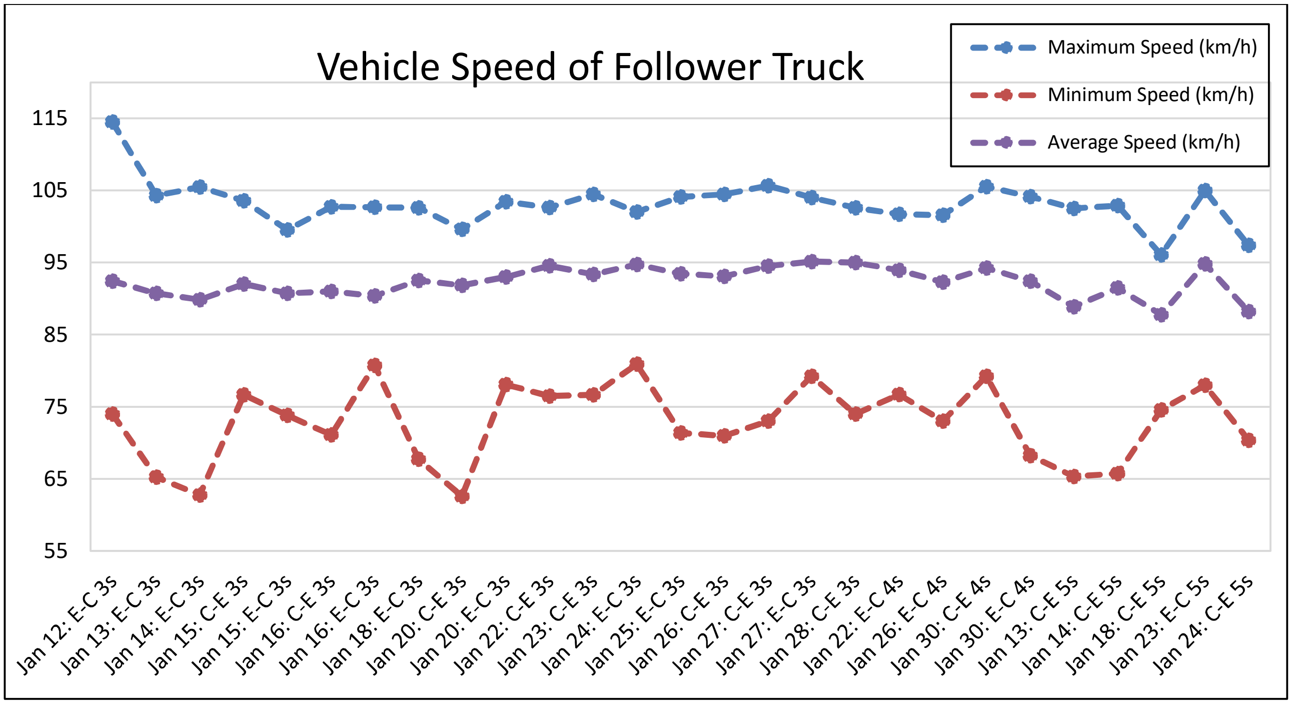


Figure 35: follower truck speed under platooning

As shown in Figure 36, the average speed for the lead truck ranged from 88.7 to 95.0 km/h. Overall, the lead and follower trucks run at similar speeds under platooning conditions with no cut-ins. Furthermore, the maximum speed of the lead truck under platooning ranged from 97.6 to 115.8 km/h, and the minimum speed ranged from 57.2 to 84.2 km/h. On the Jan 12 trip, both lead and follower trucks exceeded the maximum speed limit (i.e., 110 km/h).

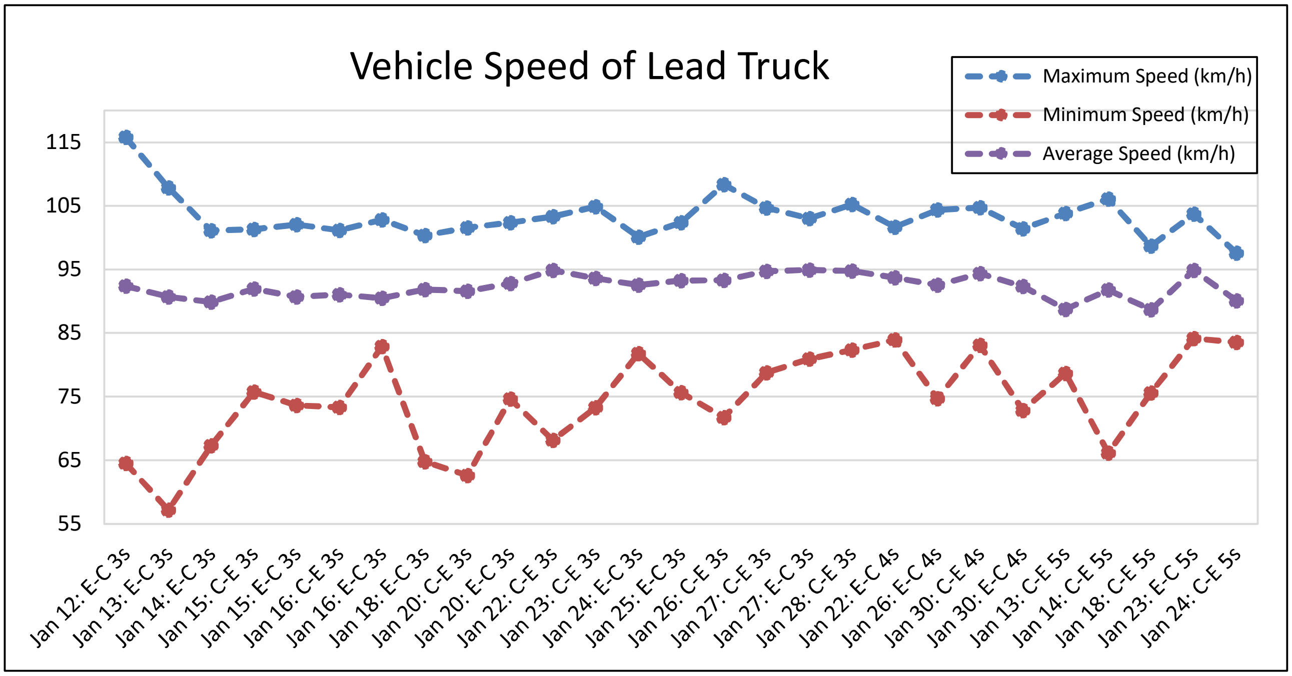


Figure 36: lead truck speed under platooning

As shown in Figure 37, the standard deviation of AB1 ranged from 2.1 to 4.8 km/h, and the average was 3.2 km/h, and the standard deviation of AB2 ranged from 2.6 to 5.9 km/h, and the average was 3.7 km/h. Furthermore, the speed of the follower truck generally had more speed fluctuations compared to that of the lead truck. Only in two trips (Jan 18: E-C 3s & Jan 23: C-E 3s), the speed standard deviation of the follower truck was less than that of the lead truck.

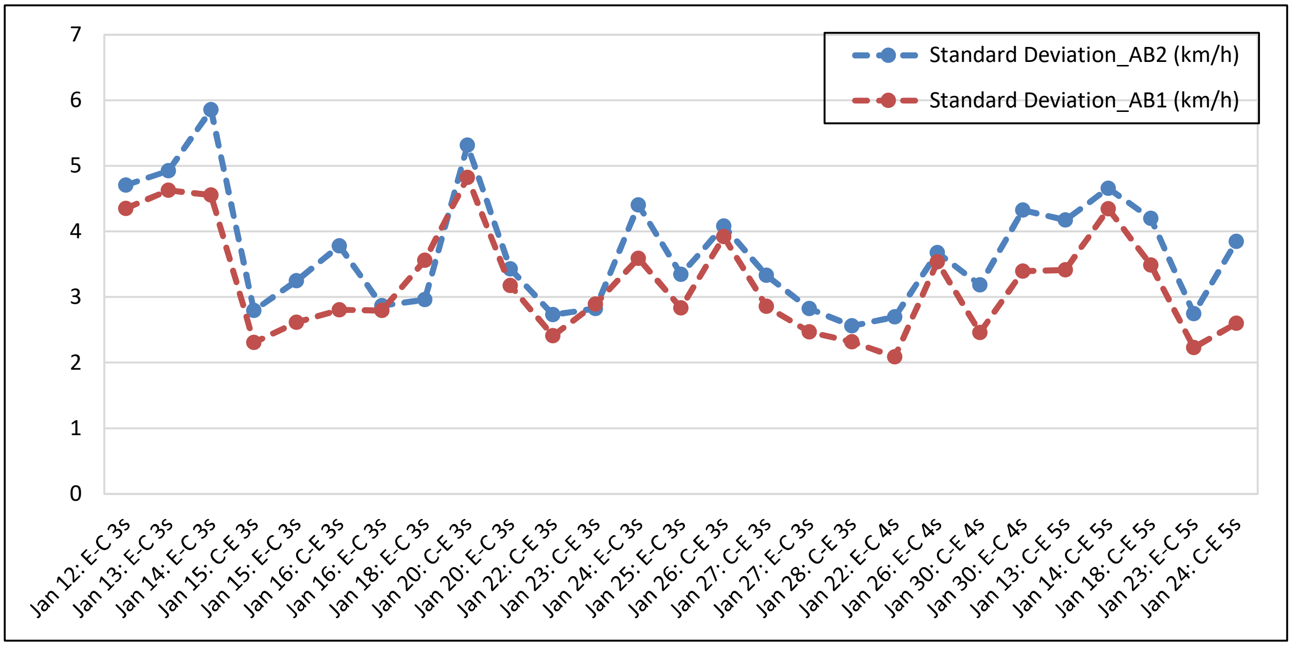


Figure 37: Comparison of standard deviation of truck speeds under platooning

Truck Acceleration/Deceleration under Platooning

During the Jan 22 (E-C), 23 (C-E), 25 (E-C), and 26 (C-E) platooning trips, the maximum acceleration was 0.40 m/s^2 in the follower truck. As shown in Figure 38, during platooning, there were 32 acceleration events ($a \geq 0.3\ m/s^2$) for the lead truck and 24 acceleration events ($a \geq 0.3\ m/s^2$) for the follower truck. Furthermore, in 60% of platooning trips with at least one acceleration event of $\geq 0.3\ m/s^2$, the follower truck had fewer high-acceleration events than those of the lead truck.

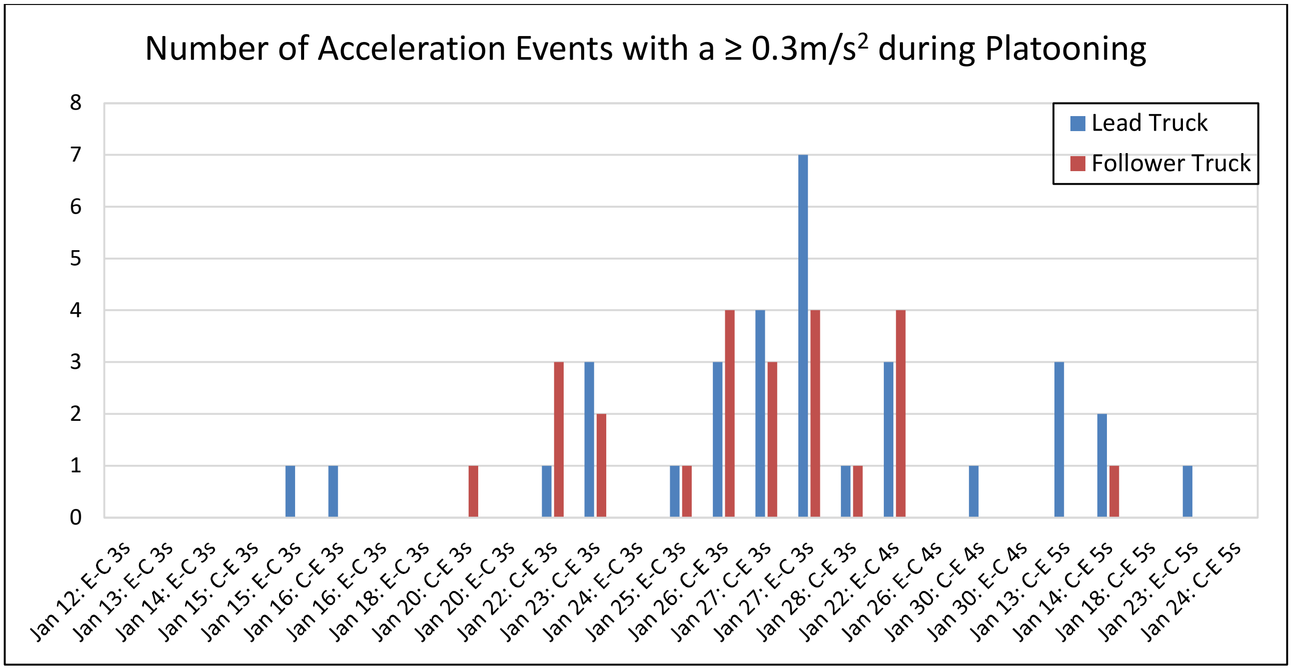


Figure 38: Number of acceleration events with a ≥ 0.3m/s2 during platooning

As shown in Figure 39, during the Jan 23 (E-C) platooning trip, the maximum deceleration event of 2.02 m/s^2 (caused by a sudden cut-in) in the follower truck. During all the trials, there were 71 deceleration events ($a \leq -0.5$ m/s^2) for the lead truck, and 147 deceleration events ($a \leq -0.5$ m/s^2) for the follower truck. Furthermore, in 73% of platooning trips with at least one deceleration event of $a \leq -0.5$ m/s^2, the follower truck had more deceleration events than those of the lead truck.

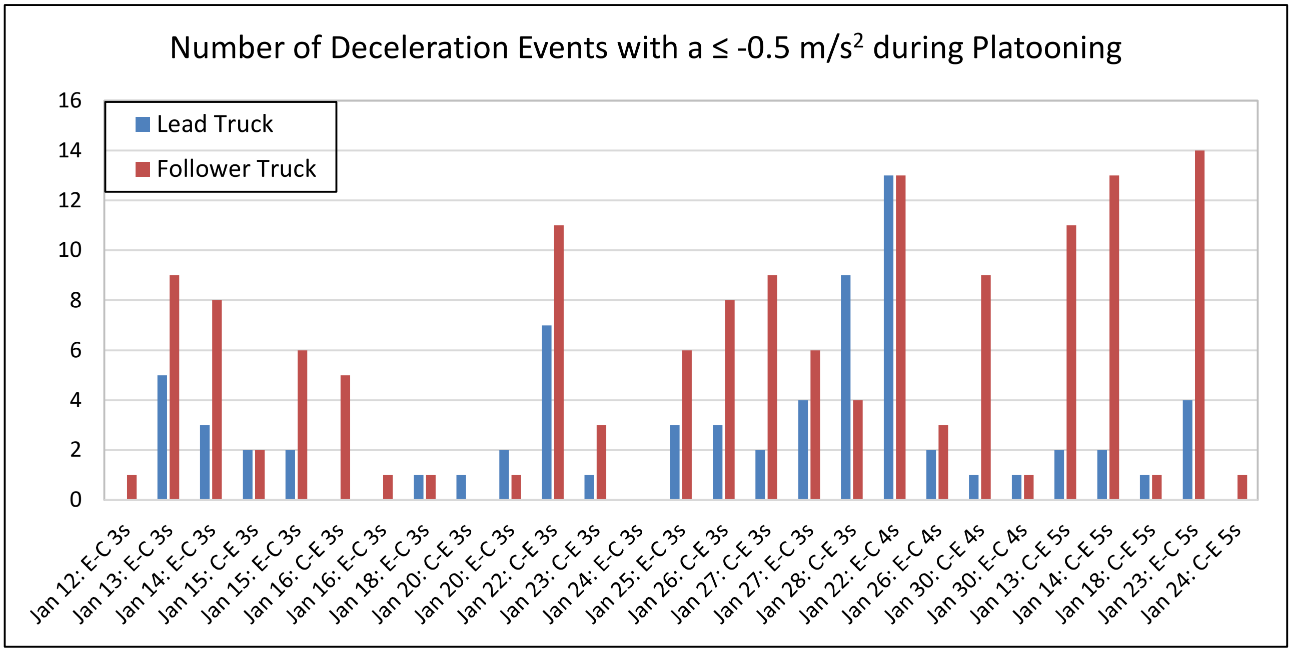


Figure 39: number of deceleration events with a ≤ -0.5 m/s2 during platooning

As shown in Figure 40, during all the trips, there were more deceleration events by the follower truck compared to the lead truck for different deceleration criteria. Furthermore, when a ≤ -2.0 m/s^2 criterion is applied, no event for the lead truck was observed.

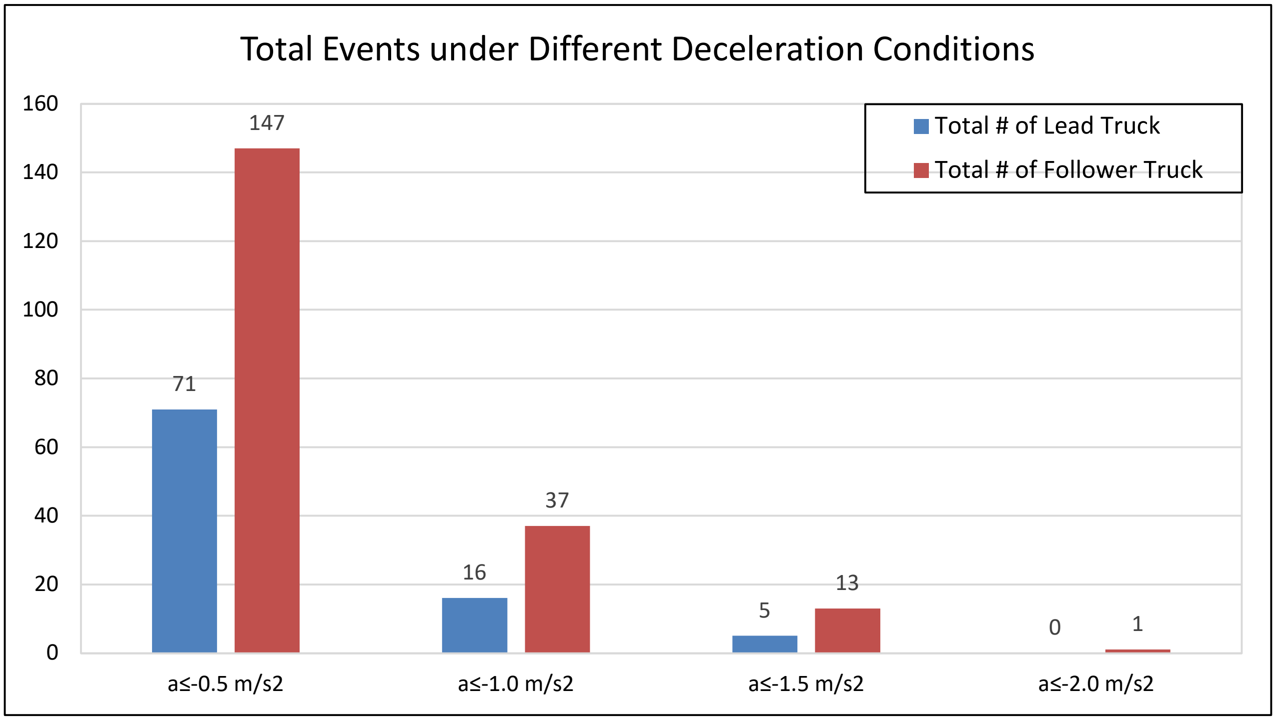


Figure 40: Total deceleration events according to different deceleration metrics

Percentage of Driver Brake of AB2 under Platooning

As shown in Figure 41, the driver brake of the follower truck under platooning ranged from 0.1% to 2.7%. Furthermore, more braking is generally observed in 5-sec commanded platooning distance vs 3-sec.

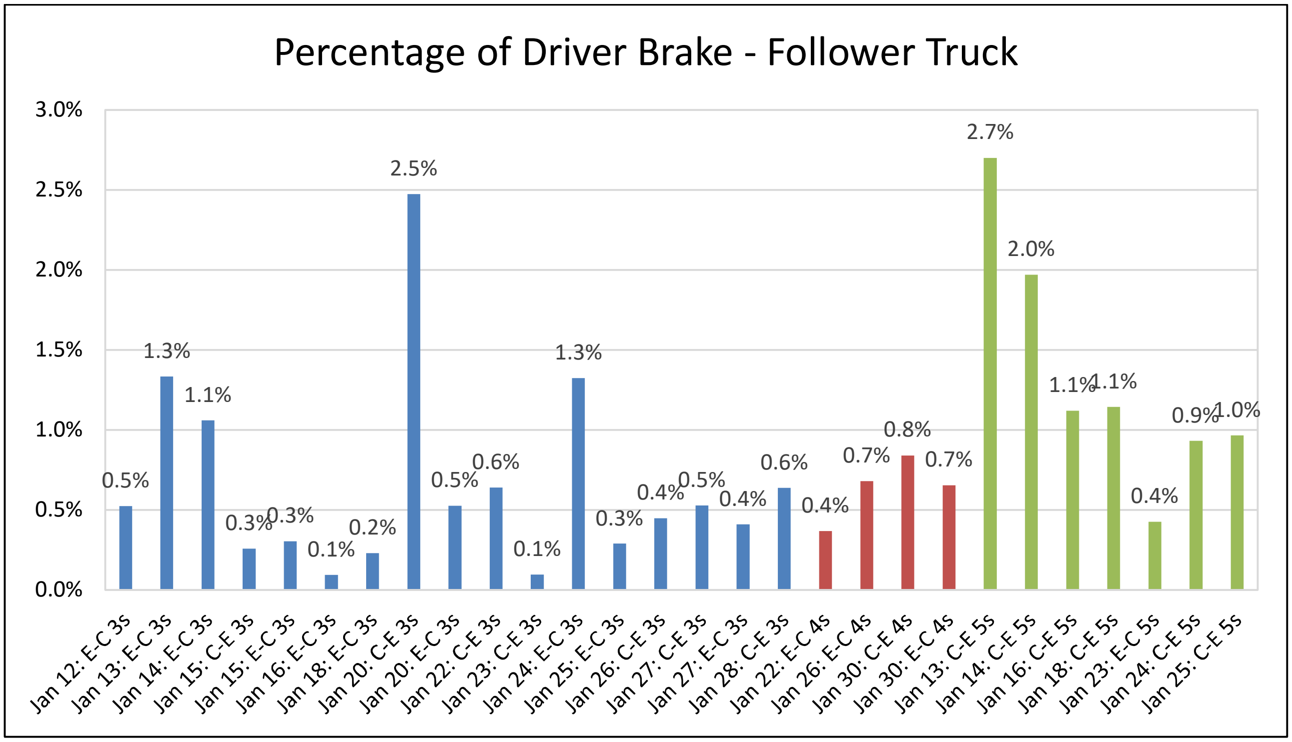


Figure 41: Percentage of driver brake of the follower truck. The percentage of driver brake of AB2 under platooning was calculated based on driver braking duration divided by the total platooning duration.

Signal Transmission Latency

During cooperative truck platooning operation, the signal such as vehicle speed and acceleration from the lead truck was continuously transmitted to the follower truck, with the aim of improving braking and acceleration performance of the follower truck. The signal transmission latency affects the platooning control system. Thus, it is important to minimize transmission latency. To this end, Figure 42 shows the average signal transmission latency between two trucks. The latency values ranged from 0.452 to 2.108 s during all platooning trips. Furthermore, the median values of latency ranged from 0.353 to 0.714 s during all platooning trips.

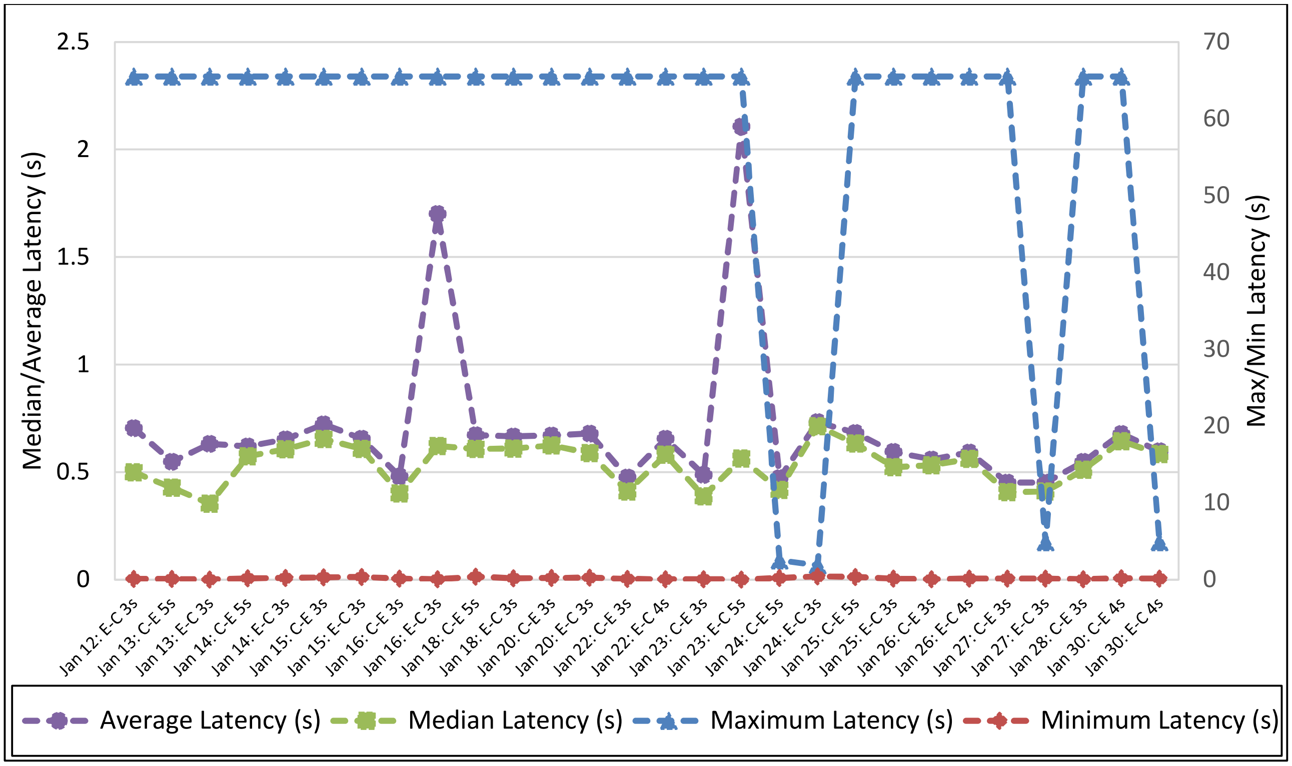


Figure 42: Link latency of signal transmission between lead and follower trucks during platooning

7. Fuel Consumption and NOx Emissions

Effect of platooning systems on fuel consumption is described in this section. The initial sections discuss the accuracy of the measurements, difference between lead and follower truck for non-platooning conditions, and the effect of weight on truck fuel consumption. These early sections provide insights to properly assess the platooning fuel consumption and associated uncertainties. The properties of the diesel fuel used for the study are found in Appendix F.

7.1. ECU Fuel Consumption Estimation vs Actual Fuel Flow Measurement

Analysis of fuel consumption behavior is based on the real time fuel consumption measurements using the AIC fuel flow meter. The AIC fuel flow meter is an accurate device and it is used for measuring fuel consumption during all the trips. Instantaneous fuel consumption graphs are meaningful when they are discussed along with other engine/powertrain parameters regarding the situation of truck in the road section.

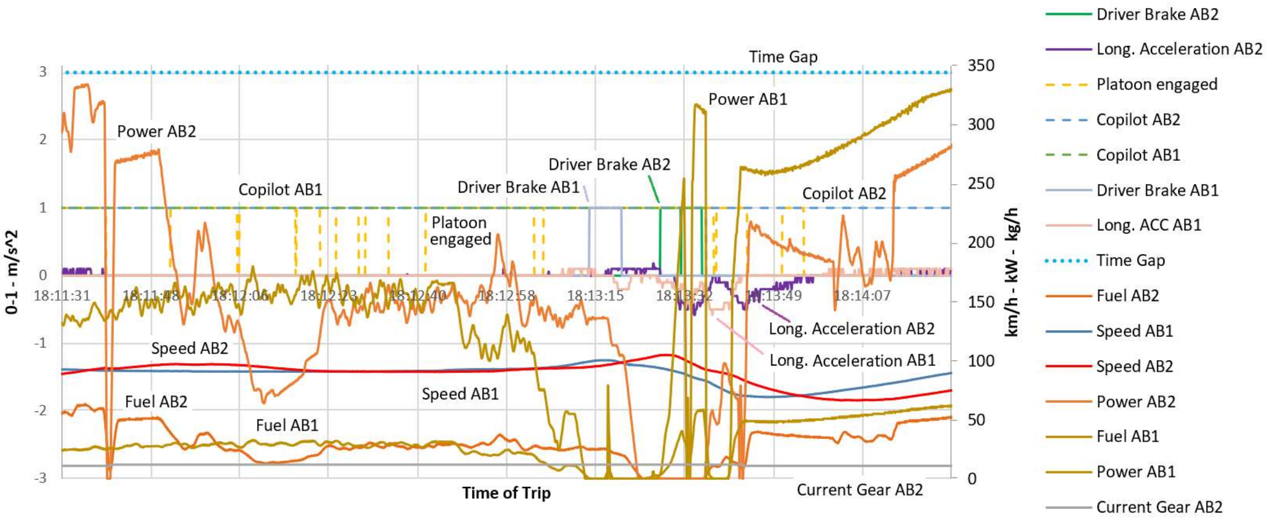


Figure 43: Typical instantaneous fuel consumption graph and platooning system parameters

Figure 43 shows a typical instantaneous fuel consumption for AB1 and AB2 including 13 more parameters to understand trucks' situational conditions. There will be more graphs like this in the later sections for describing event base analysis of the trip situation. Description of parameters on the graph is given below:

- Driver brake AB2: Parameter which appears with the value of 0 or 1 at any time. (0-1)
- Longitudinal acceleration AB2: Acceleration value is reported from truck accelerometer (m/s^2)
- Platoon engaged: From AB2 CTPS parameters stands for engagement situation (0-1)
- Copilot AB2: Stands for the time AB2 copilot is engaged (0-1)
- Copilot AB1: Stands for the time AB1 copilot is engaged (0-1)
- Driver brake AB1: Parameter which appears with the value of 0 or 1 at any time. (0-1)
- Longitudinal acceleration AB1: Acceleration value is reported from truck accelerometer (m/s^2)
- Time gap: Time gap setting (3, 4, 5 sec)
- Fuel AB2: Instantaneous fuel consumption of AB2 truck reported from engine ECU
- Speed AB1: Lead truck speed
- Speed AB2: Follower truck speed
- Power AB2: Instantaneous power reported from engine ECU
- Fuel AB1: Instantaneous fuel consumption of AB1 truck reported from engine ECU
- Power AB1: Instantaneous power from engine ECU
- Current gear AB2: Stands for the current gear transmission system of AB2

The fuel flow meter was installed on the upstream of the fuel line which gets the fuel from fuel tank and passes it to the engine. There was a water separator between the AIC flow meter and the engine. Water separators always have an empty cavity filled with air, the air-filled volume acts like a compressible media and make the fuel flow dependent on a range of pressure difference. This issue causes time delay for instantaneous fuel consumption measurement. Instantaneous fuel consumption estimation from the engine ECU (SAE J1939) is reviewed in Figure 44.

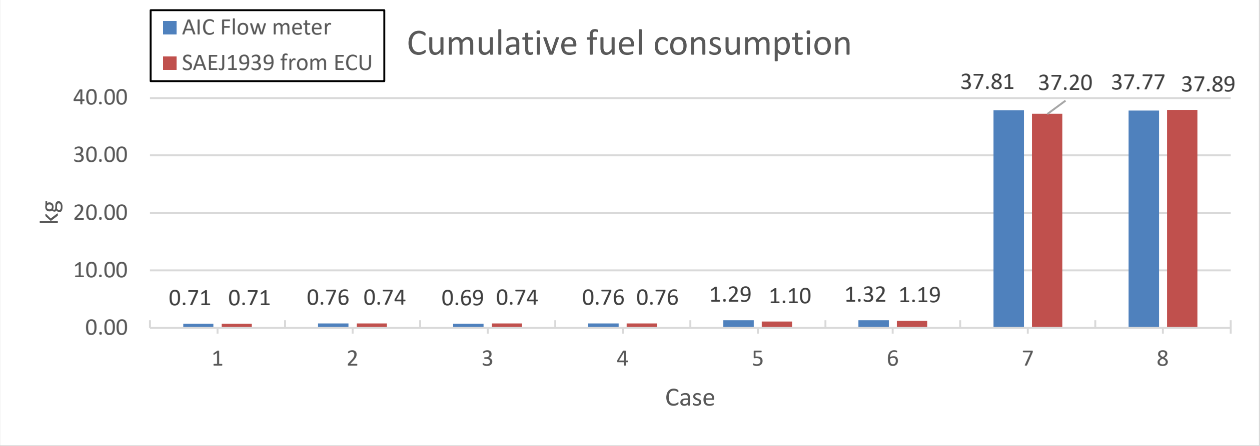


Figure 44: SAE J1939 (engine ECU) fuel consumption reported values in comparison with AIC flow meter values

Cases 1, 2, 3 and 4 in Figure 44 include sections with the length of 3 km. Case 5 and case 6 are the sections with 5 km length. Cases 7 and 8 are for the sections of road with 140 km length. The maximum and minimum difference between AIC and ECU reported values are 14% (case 5) and 0.3% (case 8) respectively. Instantaneous fuel consumption graphs from engine ECU are meaningful to be used for showing the trend. In this report all the fuel consumption values are reported from the AIC flow meters, except for the cases indicated.

7.2. Idling fuel consumption

The number of idling hours of the engine typically increases in the winter due to factors such as cabin heating and the required time for the engine to reach a fully warmed up condition (i.e., $T_{coolant}$ > 80 °C). Recorded data shows that idling fuel consumption for Peterbilt trucks with Cummins X15 engine at fully warmed up condition during the tests in January was about 2.45 kg/h (Figure 45).

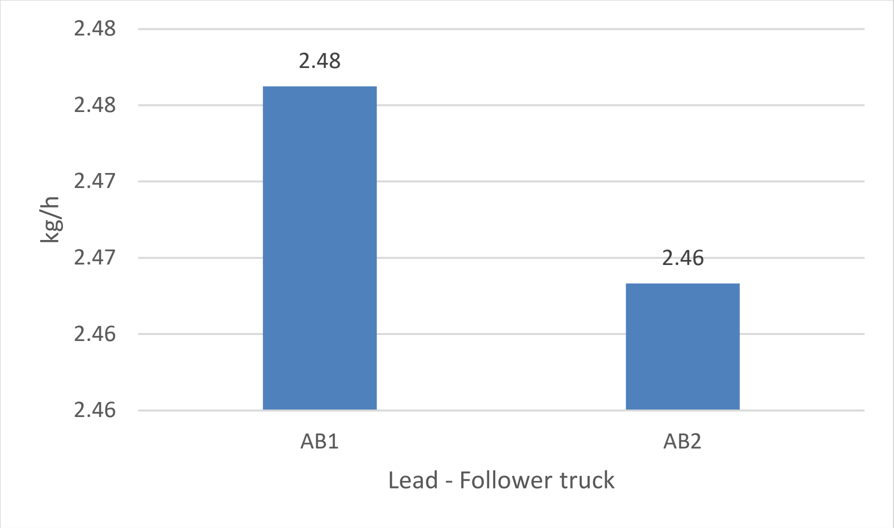


Figure 45: Idling fuel consumption for AB1 and AB2 trucks at engine fully warmed up condition (i.e., Tcoolant= 82 to 95 °C)

7.3. Non-platooning fuel consumption comparison between lead and follower trucks

Fuel consumption of identical make and model of trucks can be different from each other due to manufacturing variability and potential differences between powertrain systems. For the two Peterbilt trucks, AB2 had 14,000 km more mileage compared to AB1 before starting the trip on 13th of Jan 2022. The difference between fuel consumption of the lead and follower trucks can make the situation complex about the comparison of fuel consumption in platooning. The effect of copilot and platooning control system on fuel consumption can make the situation better or worse. Thus, it is important that the effect of platooning and the effect of difference between powertrain systems in the two trucks to be separated from each other. To this end, non-platooning fuel tests were carried out. These include tests were conducted on Dec. 10, 2021 and Jan. 31, 2022.

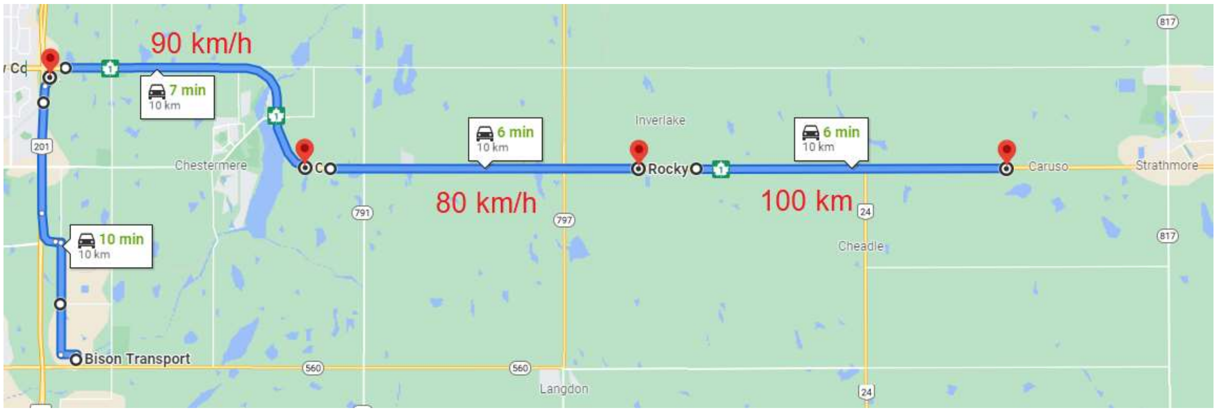


Figure 46: On road path of trucks for Dec 10 2021 fuel tests under non-platooning conditions at three different speeds

Dec 10th 2021 tests for fuel consumption were done on Highway 1 from Calgary to Strathmore. The path for the trucks and the truck speed at each section is shown in Figure 46. Jan 31st 2022 tests for fuel consumption were done on a route near Bison transport yard from Calgary to Langdon. The path for the trucks is shown in Figure 47.

This fuel consumption test was planned for the last day of the January trials, unfortunately, that day was too windy. Due to high wind conditions on Jan 31, those tests only included tractor only (bobtail) fuel consumption tests. The result of specific fuel consumption is presented in Figure 48.

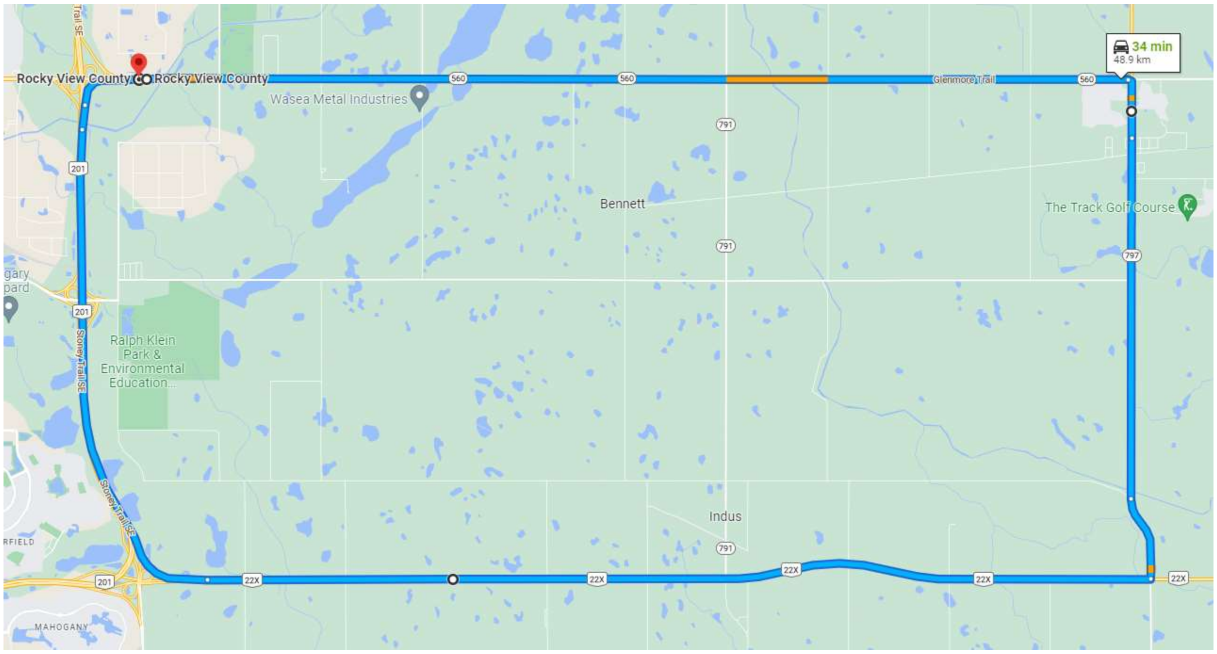


Figure 47: On road path of trucks for bobtail fuel test on 31st of Jan. 2022 under non-platooning conditions at three different fixed speeds

In Figure 48, comparisons of specific fuel consumption for the two trucks at the loaded condition and tractor only configuration are shown. In the test for tractor only configuration on Jan 31 the weights of the trucks were equal. For the Dec 10 tests with trailer, the same trailer for both trucks was used. For both non-platooning tests the AB1 tractor had consumed more fuel.

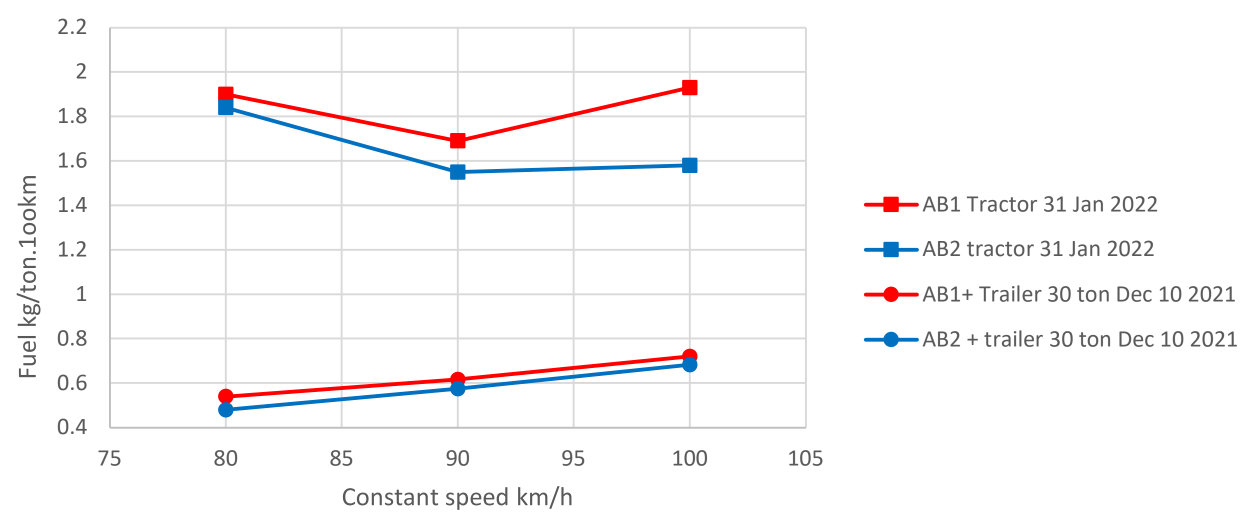


Figure 48: Comparison of specific fuel consumption of both trucks under non-platooning conditions.

The results for comparing fuel consumption at three fixed speeds (i.e., 80, 90, 100 km/h) for on-road tests are provided in Table 13.

Table 13: Comparison of fuel consumption of trucks at constant speeds

Dec 10 2021	80 km/h	90 km/h	100 km/h
Tractor + loaded Trailer (AB1 consumes more)	12%	7%	6%
Jan. 31 2022	80 km/h	90 km/h	100 km/h
Tractor only (AB1 consumes more)	3%	9%	22%

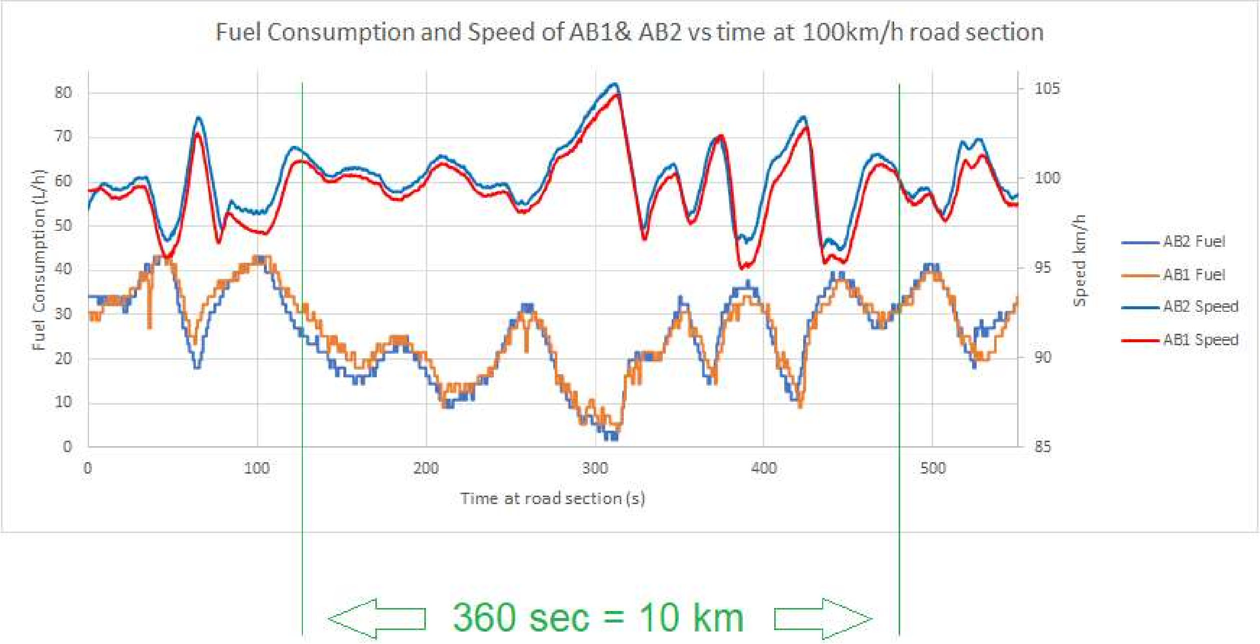
$$\Delta m_{fuel}(\%) = \frac{m_{fuel}(\mathrm{AB1}) - m_{fuel}(\mathrm{AB2})}{m_{fuel}(\mathrm{AB2})} \times 100\% \tag{2}$$

Where,

$m_{fuel}(\mathrm{AB1})$ = Cumulated fuel consumption of the lead truck during the given section of trip;

$m_{fuel}(\mathrm{AB2})$ = Cumulated fuel consumption of the follower truck during the given section of trip.

Transient fuel consumption for the 100km/h road section of Dec 10 test is shown in Figure 49. As shown in the figure, the transient fuel consumption of AB2 truck is less than that of AB1 for the most part. This is supporting the values presented in Table 13. Overall, it is difficult to compare fuel consumption of every single point of the road; that is the reason of comparing the cumulative fuel consumption in a similar section. There is about 0.5 km/h difference between speeds of the trucks as seen in Figure 49.


Fuel Consumption and Speed of AB1& AB2 vs time at 100km/h road section

360 sec = 10 km

Figure 49: Transient fuel consumption for 100 km/h section of Dec 10 2021 test

7.4. Extracting the engine specific fuel consumption map

Specific fuel consumption of the trucks depends on engine load and speed. We wanted to understand how the engine operating conditions change during platooning, how payload weight affects the engine operating conditions and consequently affects the truck fuel consumption. To this end, a specific fuel consumption (g/kW.hr) map of the engine as a function of engine speed and load (torque) was needed. Normally, the engine manufacturers don't publish detailed information such as an engine brake specific fuel consumption (BSFC) map. As a result, we used the existing data from non-platooning baseline trials to generate the BSFC map.

After analyzing the various engine working points during the non-platooning trials, data of more than 3000 points were utilized to create a contour map for the engine BSFC. Figure 50 shows the extracted BSFC map of the Cummins X15 engine. The most efficient fuel consumption zone is located around the working point of 1400-1600 Nm and 1100 rpm. In this region, the engine has the highest brake thermal efficiency leading to the specific fuel consumption of 190g/(kW.hr). This BSFC map explains how engine efficiency (i.e., 1/BSFC) drops by running the engine at low torque or high-speed conditions.

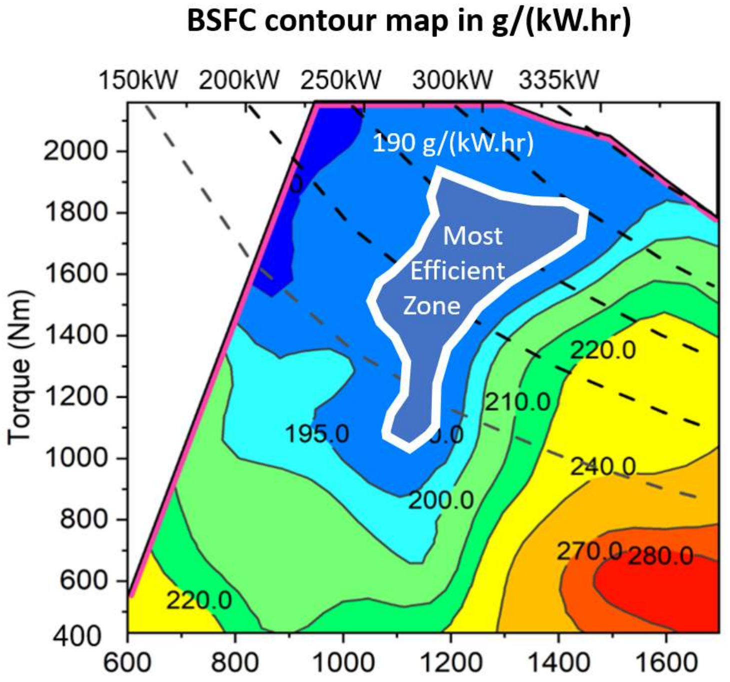


Figure 50: Engine brake specific fuel consumption map extracted from collected engine data

7.5. Effect of truck weight on fuel consumption under non-platooning operation

The CTPS trials included truck operation with commercial loads with varying weights as previously shown in Figure 23. These included trips that range from empty trailer operation to a fully loaded trailer with vehicle weight of 39.3 ton. We wanted to understand the effect of truck weight on fuel consumption of the truck, so we can separate the weight effect from the platooning effect on the truck fuel consumption. In order to study the sole effect of weight on truck fuel consumption, we analyzed the truck data under non-platooning conditions with a same truck with different weights.

We tested the truck at different fixed speeds on a same path shown in Figure 51 for both tractors only and tractor plus the trailer configuration. The test was done within two hours of time difference on the same day. The location of the section of road is on Highway 16 from west to east near Bison Transport's Edmonton yard on a known section of road with known grading characteristics.

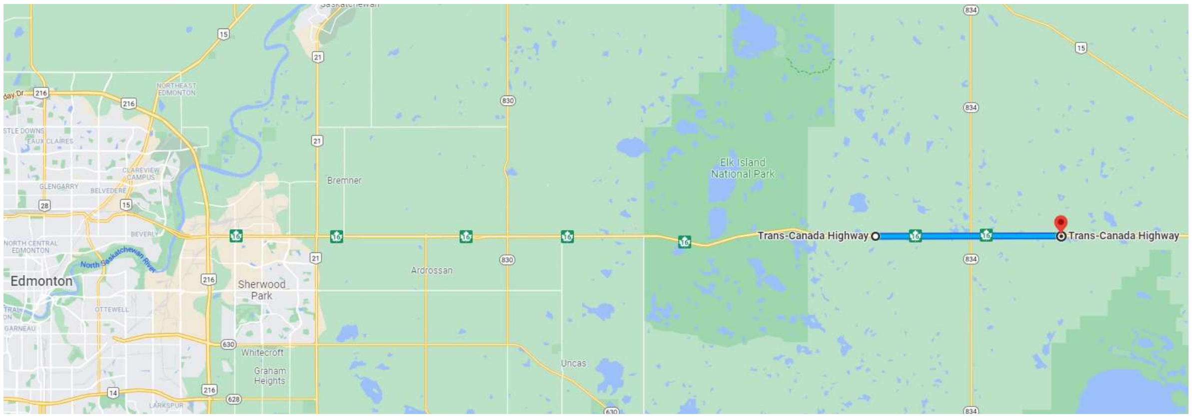


Figure 51: The path for 23rd of Nov 2021 non-platooning fuel consumption tests

Figure 52 shows the graph of speed and road grade over time from non-platooning fuel consumption test shown in Figure 51. The truck speed was set for 100 km/h under cruise mode. As expected, more speed fluctuations were observed when the truck was loaded compared to tractor only operation. This was due to tractor and trailer dynamics and higher wind influence on combined tractor and trailer compared to tractor only.

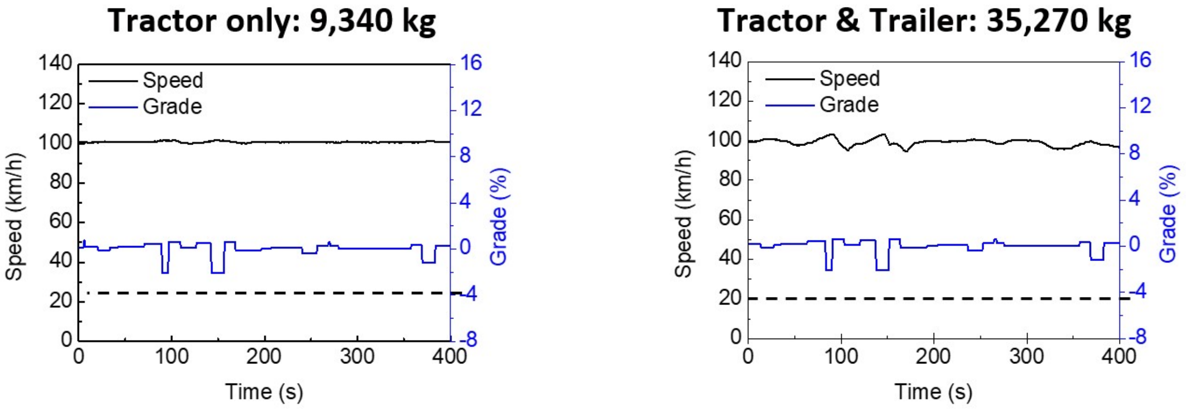
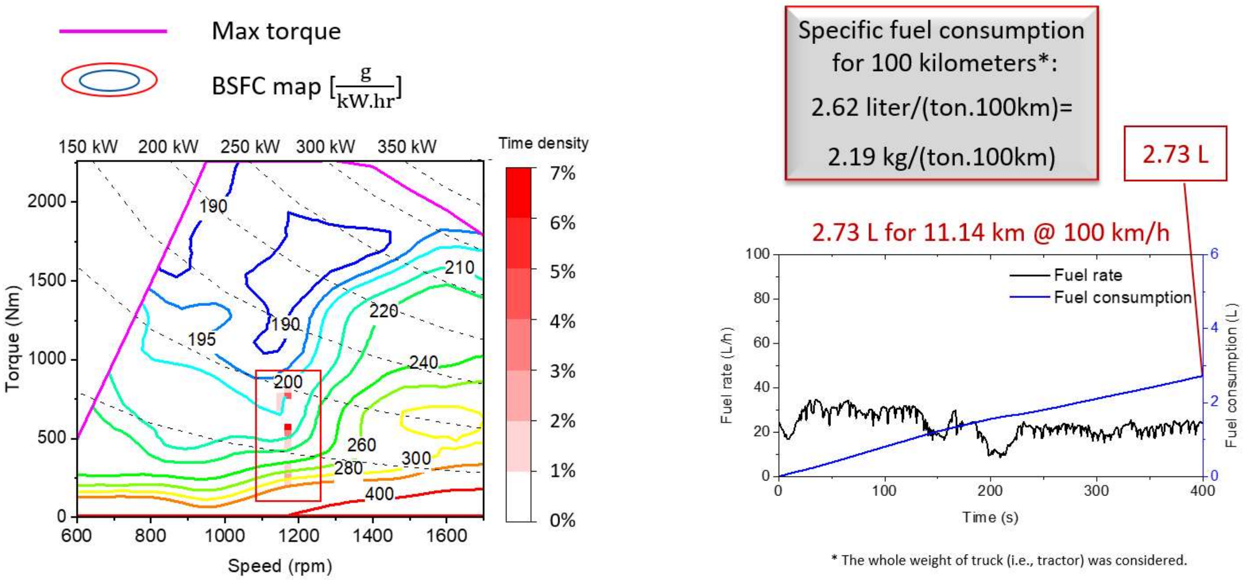


Figure 52: Truck speed and road grade for 23rd Nov 2201 test for: tractor only (left plots), and combined tractor and trailer (right plots)

To characterize the operating conditions on the power train system of the truck, the data from non-platooning tests were used. Cruise test data for tractor only is shown in the Figure 53.

Figure 53 and Figure 54 show the truck fuel consumption under two different weights. The results show the specific fuel consumption of the truck in terms of kg/(ton.100 km) is 3.3 times less when the truck weight is increased from 9340 kg to 35270 kg. This can be explained by looking at the engine operating points in the BSFC map, as shown in the left plots in Figure 53 and Figure 54. Comparing the engine operating points for both tests, we can see for the heavier truck, the engine operation points are more concentrated at the higher efficiency zone in the BSFC map. That is the reason for better specific truck fuel consumption for the heavier truck. This is mainly because the engine is calibrated to operate most efficiently at target load conditions of a near fully loaded truck. But when a truck's weight is substantially less than the truck rated weight, the truck engine will mostly operate in the low-efficiency zone in the BSCF map.



Specific fuel consumption for 100 kilometers*:

2.62 liter/(ton.100km)=

2.19 kg/(ton.100km)

* The whole weight of truck (i.e., tractor) was considered.

Figure 53: Tractor only fuel consumption; Left plot: Engine BSFC map along with engine operating conditions and time percentage spent at each condition; Right plot: instantaneous, cumulative and truck's specific fuel consumption for the cruise test at 100 km/h. *The whole weight of the vehicle is used in the calculation.

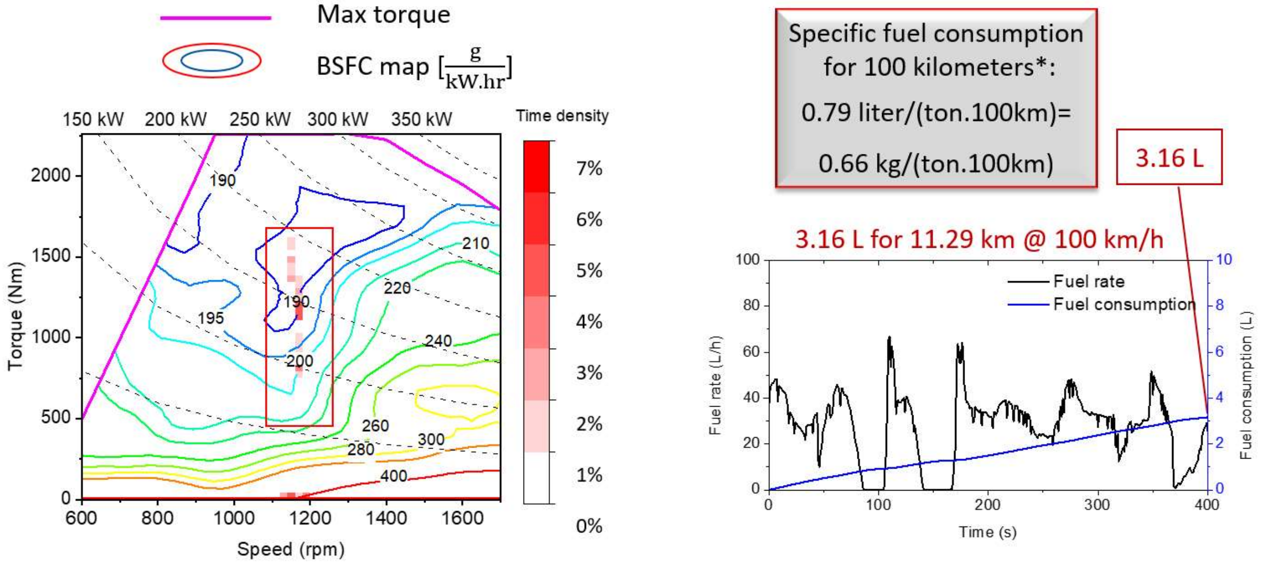


Figure 54: Tractor and loaded trailer fuel consumption; Left plot: Engine BSFC map along with engine operating conditions and time percentage spent at each condition; Right plot: instantaneous, cumulative and truck's specific fuel consumption for the cruise test at 100 km/h. *The whole weight of the vehicle is used in the calculation.

7.6. Platooning Fuel Consumption

To properly assess the effect of platooning on fuel saving by the follower truck, a third truck denoted as the "control truck" is typically needed according to SAE J1321 standard. However, given the platoon distance between the lead and follower trucks in this study was substantial (i.e., 3 ≥ sec), the lead truck was used as the "control truck" and served as the baseline. The validity of this approach was confirmed with the NRC team[3] that had significant prior experience for fuel consumption studies for truck platooning. Each truck had a different weight; thus, the reported fuel consumption values were normalized based on truck weights for proper comparison.

In addition, part of fuel consumption analysis included segment-wise fuel consumption assessment to investigate variations in fuel consumption as a result of certain driving maneuvers (e.g., due to cuts-in by a neighboring vehicle). In this analysis, fuel consumption of the follower truck was compared against itself for a similar driving condition when the platoon was engaged. This analysis became possible since we collected "instantaneous" fuel consumption instead of just reporting a cumulative fuel consumption for the whole trip. Finally, we could determine engine fuel consumption as a function of engine speed and load and then compare the engine operating points on the fuel consumption map under platooning and non-platooning conditions.

Figure 55 (a) shows the accumulated fuel consumption on specific trip distances of the road. In this graph specific fuel consumption of both trucks is shown. To have better understanding, the truck weights are also shown on this graph since weight is a critical factor on truck specific fuel

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[3] McAuliffe, B., Lammert, M., Lu, X., Shladover, S. et al., "Influences on Energy Savings of Heavy Trucks Using Cooperative Adaptive Cruise Control," SAE Technical Paper 2018-01-1181, 2018, https://doi-org.login.ezproxy.library.ualberta.ca/10.4271/2018-01-1181.

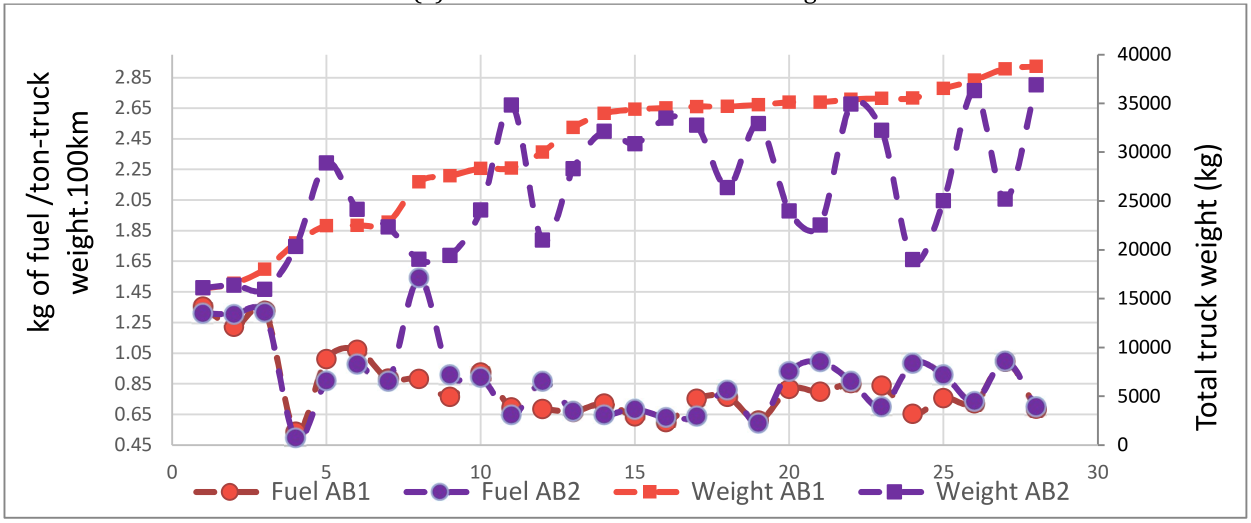
consumption as explained in the previous section. Trips are sorted based on the ascending weights of AB1. So, the trips in which AB1 had lower weight are shown at left side of the chart. Meanwhile the weight of AB2 is showing an oscillating behavior because of different commercial loads but, in some of the trips AB2 weight has been almost equal to AB1. Trips with an empty trailer have higher specific fuel consumption, as expected.

Specific fuel consumption in Figure 55 varies from about 0.5 to 1.3 kg/ton of truck over 100 km. For the heavy configurations, specific fuel consumption gets close to the values of 0.65kg/(ton.100km). The behavior of the fuel consumption graph is irregular due to day-to-day changes due to weight, traffic and wind variations.

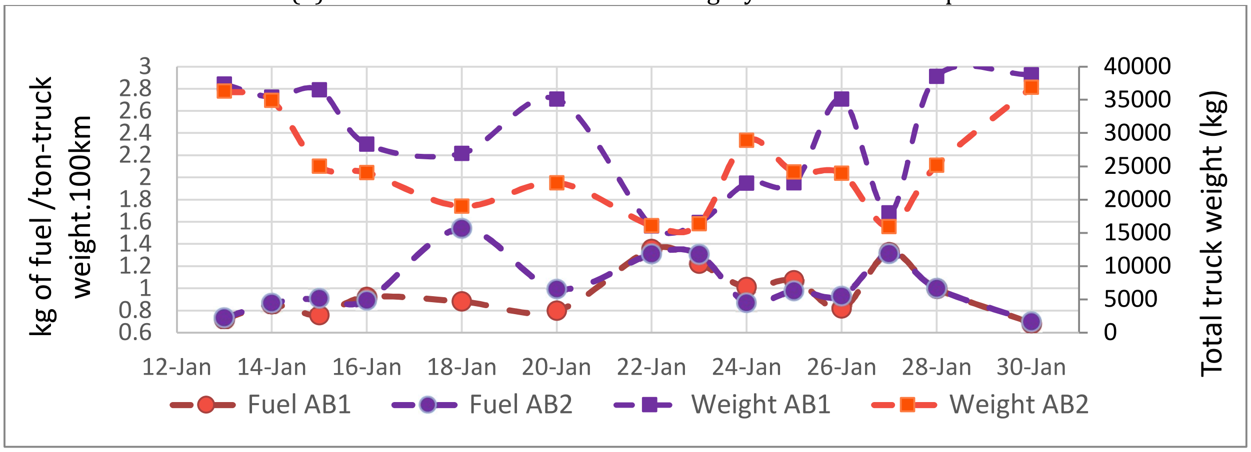
In order to review the difference between the trips from Edmonton to Calgary and the trips from Calgary to Edmonton, separate fuel consumption graphs are included. Fuel consumptions for the trips from Calgary to Edmonton are shown in Figure 55(b). Fuel consumption for these trips are in the range of 0.5 to 1 kg/ton.100km. In comparison we see an average difference of 0.2 kg/ton.100 km. In Figure 55(c) we can see the fuel consumption from Edmonton to Calgary. Average of the fuel consumptions for these trips are about 0.7 to 1.4 kg/ton.100km. Trips from Edmonton to Calgary use more fuel because the altitude of Edmonton is 378 m less than that of Calgary.

Results in Figure 55 show the truck weight is the dominant factor. When there is a substantial weight difference between the lead and follower trucks, the specific fuel consumption (kg/ton.100km) of the heavier truck is lower than the other truck for a trip. To this end, the trucks with a similar weight provide important data to help understand the effect of platooning on reducing or increasing fuel consumption. A strong trend is not observed in Figure 55 since for some of the trips the lead truck consumes more fuel than the follower truck with a similar weight, but for some other trips the trend is opposite. However, by considering the results in Section 7.3, we conclude the follower truck has generally more fuel consumption compared to the lead truck during platooning. This is because the lead truck consumes more fuel than the follower truck under normal (non-platooning) conditions due to the differences between lead and follower truck. Thus, **platooning conditions (under the settings of this study) has demonstrated increased fuel consumption of the follower truck when compared to the {control} lead truck**. This could be due to the fact that the lead and follower trucks had an average effective distance of over 4 sec (i.e., > 100 m) during platooning trips. Thus, there is no substantial benefit from platooning for the aerodynamic drag reduction for the follower truck. Then the only potentially expected benefit from trials in this project could be smooth speed profiling by cooperative platooning. But as discussed before and also elaborated further in the engine power analysis, the power profile and speed profile of the follower truck is not as smooth as the lead truck. Thus, smooth speed profiling could not be achieved. This evidence results in having higher fuel consumption in the follower truck compared to that of the {control} lead truck.

(a) Data sorted based on truck weight



(b) Data sorted based on dates of Calgary to Edmonton trips



(c) Data sorted based on dates of Edmonton to Calgary trips

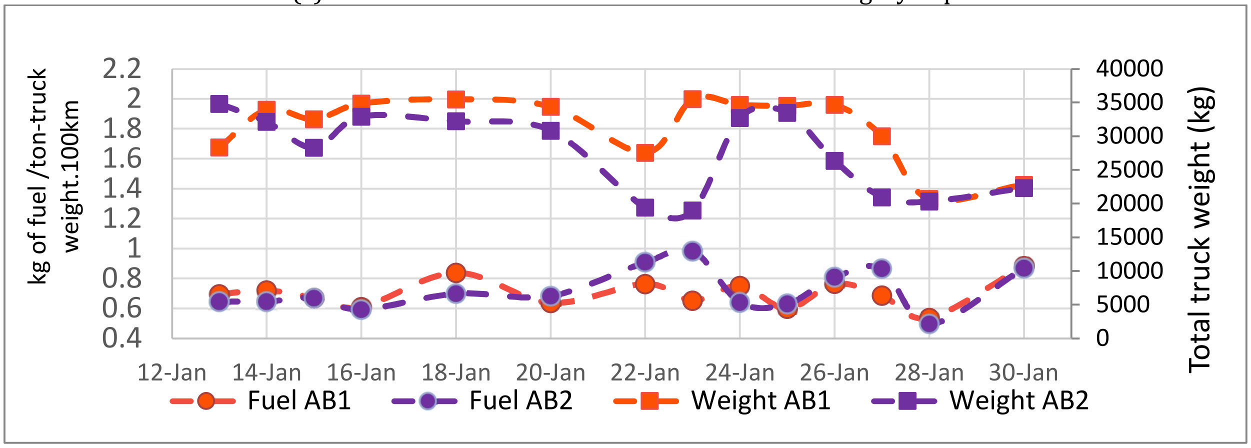


Figure 55: Cumulative specific fuel consumption of lead and follower trucks during platooning

7.7. NOx emission data

Peterbilt trucks used in this project each had two NOx sensors. The first NOx sensor is located before the aftertreatment system (measures engine-out NOx) and the next NOx sensor is located after the exhaust aftertreatment system which measures tailpipe NOx. Locations of both sensors are shown in Figure 56. Data from both NOx sensors were captured during all the trips. Instantaneous NOx emission data was measured in ppm. Here, cumulative NOx emission data is presented.

The aftertreatment system of the two trucks had different conversion efficiency. The AB1 aftertreatment system had better conversion efficiency compared to that of AB2 truck. Therefore, comparing tailpipe NOx in platooning trips was complex and not presented in this report.

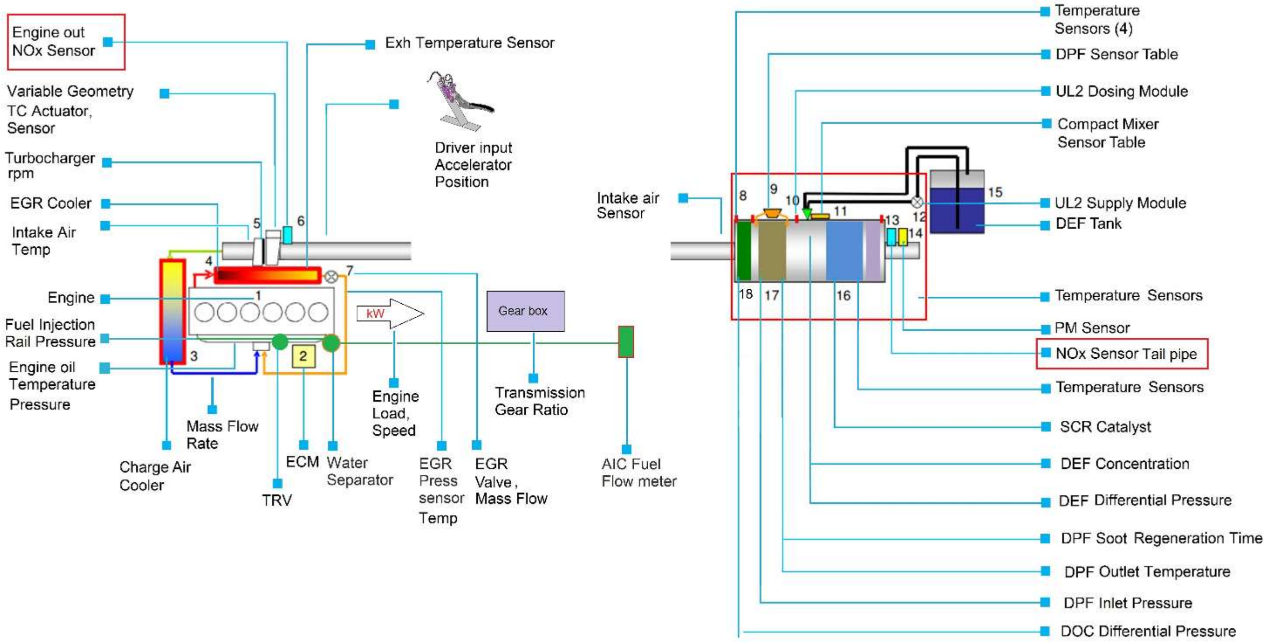


Figure 56: Locations of NOx sensors in the exhaust aftertreatment system of the truck in this study. The original image from Cummins was modified to reflect the data collected during this project via SAEJ1939 data portal

Extracting Experimental Engine-out NOx Map

Similar to efforts to create the engine BSFC map, we aimed to create a NOx map for the Cummins engine as a function of engine speed and load. This allows us to understand how engine NOx values change in the engine map during platooning. To create NOX map, data from non-platooning trips was used. After analyzing the various engine working points during the non-platooning trials, data from several thousand points (Figure 57) was used to create a contour plot NOx map in terms of g/(kW.hr). Figure 58 shows the extracted NOx map of Cummins X15 engine. Most of the engine operation during highway driving is located in the zones with NOx emissions ranging from 2 to 4 g/(kW.hr).

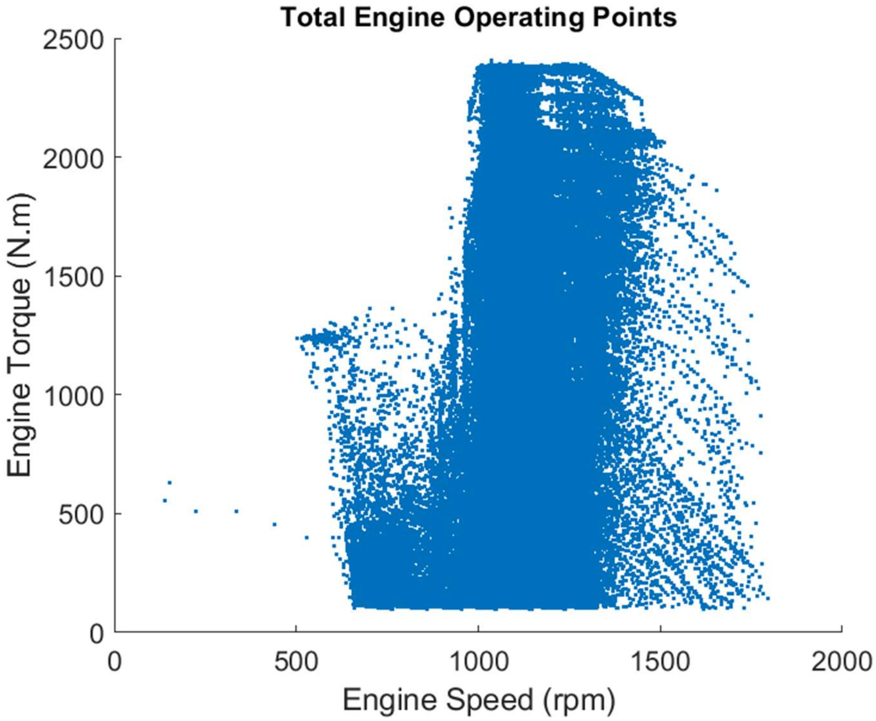


Figure 57: Experimental engine operating points used to extract the engine NOx map

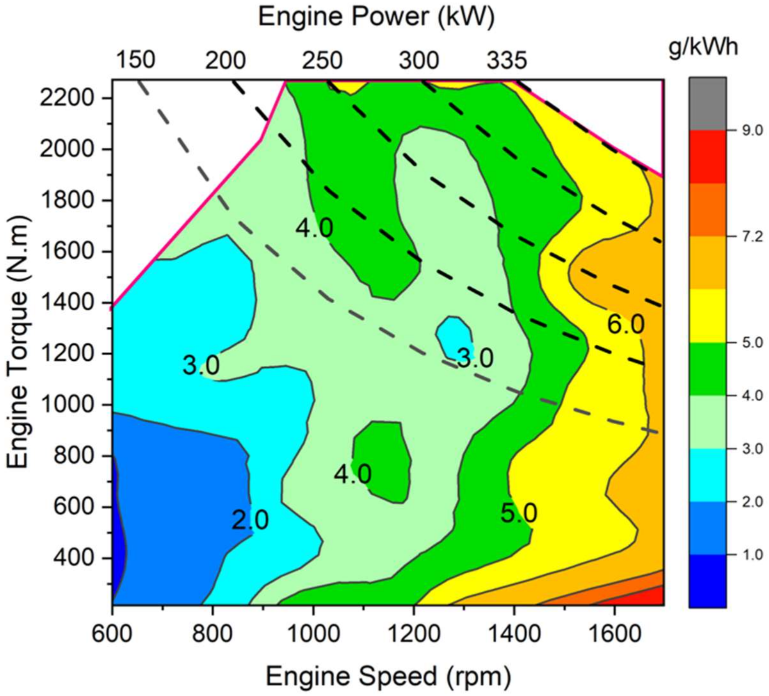


Figure 58: Specific NOx Map of X15 engine extracted from experimental on-road test data

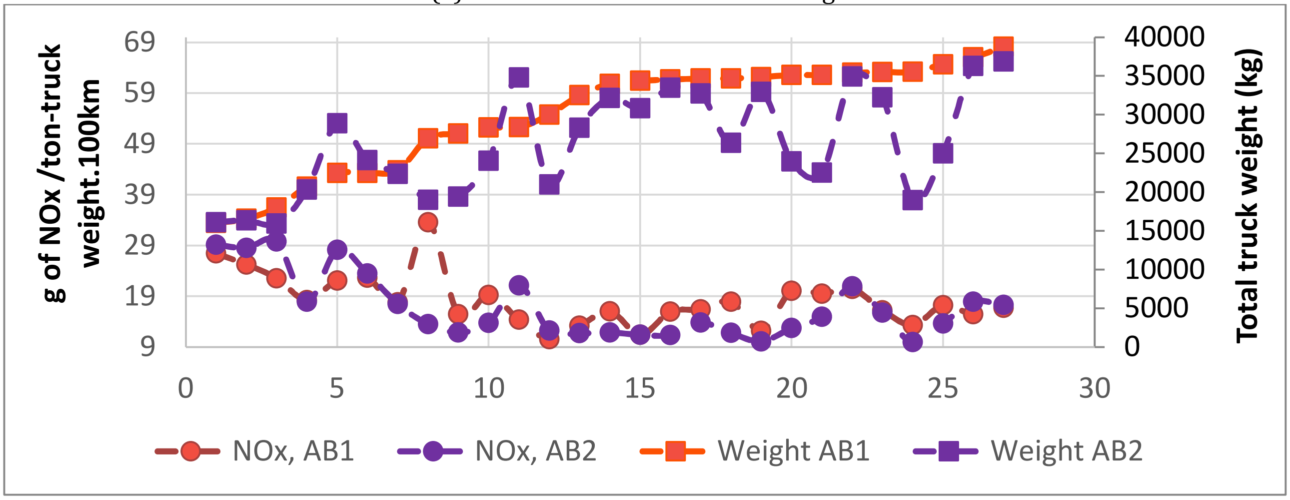
NOx emissions in platooning tests

Figure 59 shows the accumulated specific NOx during platooning trials. In this Figure specific NOx emission and weights of both trucks are shown. Trips are sorted based on ascending weight of AB1 in Figure 59(a). Trips with empty trailer (light truck arrangement) showed higher specific NOx. Specific NOx varies from about 10 to 34 g/ton of truck over 100 km. For the heavy configurations, specific NOx gets close to the values of 10 g/(ton.100km). In addition, the data is also presented by sorting based on trips from Edmonton to Calgary and Calgary to Edmonton.

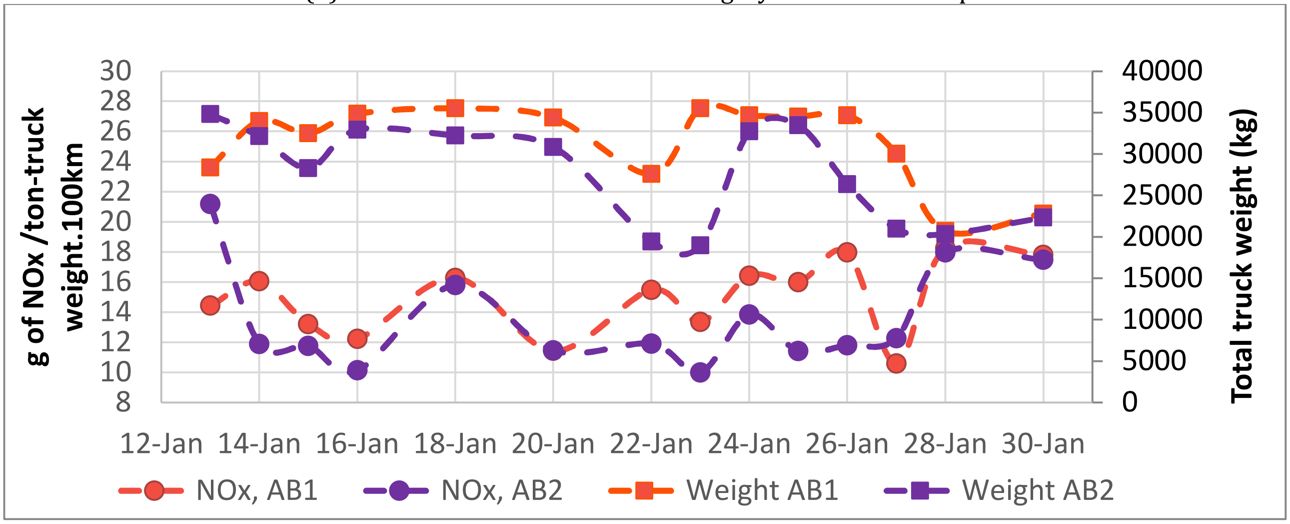
Specific NOx for the trips from Calgary to Edmonton are shown in Figure 59(b). Specific NOx values for these trips are in the range of 9 to 18 g/(ton.100km) except for one trip with 21.2 g/(ton.100km). Specific NOx for the trips from Edmonton to Calgary are shown in Figure 59 (c) the range from 13 to 34 g/(ton.100km). Trips from Edmonton to Calgary show higher specific NOx compared to the reverse path (i.e., from Calgary to Edmonton). This could be caused by difference in the engine operating points since Edmonton's altitude is 378 m less that of Calgary.

When the weight of the lead and follower trucks are substantially different, we can see the lighter truck has lower specific NOx emissions. Thus, weight of a truck is the dominant factor affecting engine-out specific NOx emissions. This should be due the effect of a truck weight on engine operating points. For trucks with a similar weight, no strong trend is observed for the effect of platooning on NOx emissions.

(a) Data sorted based on truck weight



(b) Data sorted based on dates of Calgary to Edmonton trips



(c) Data sorted based on dates of Edmonton to Calgary trips

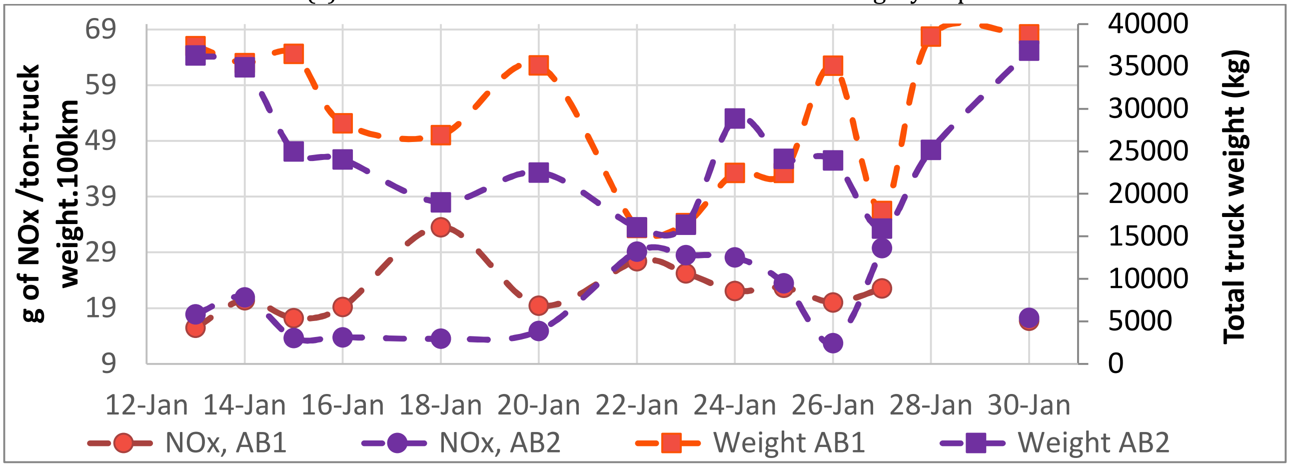


Figure 59: Engine-out NOx emissions during platooning

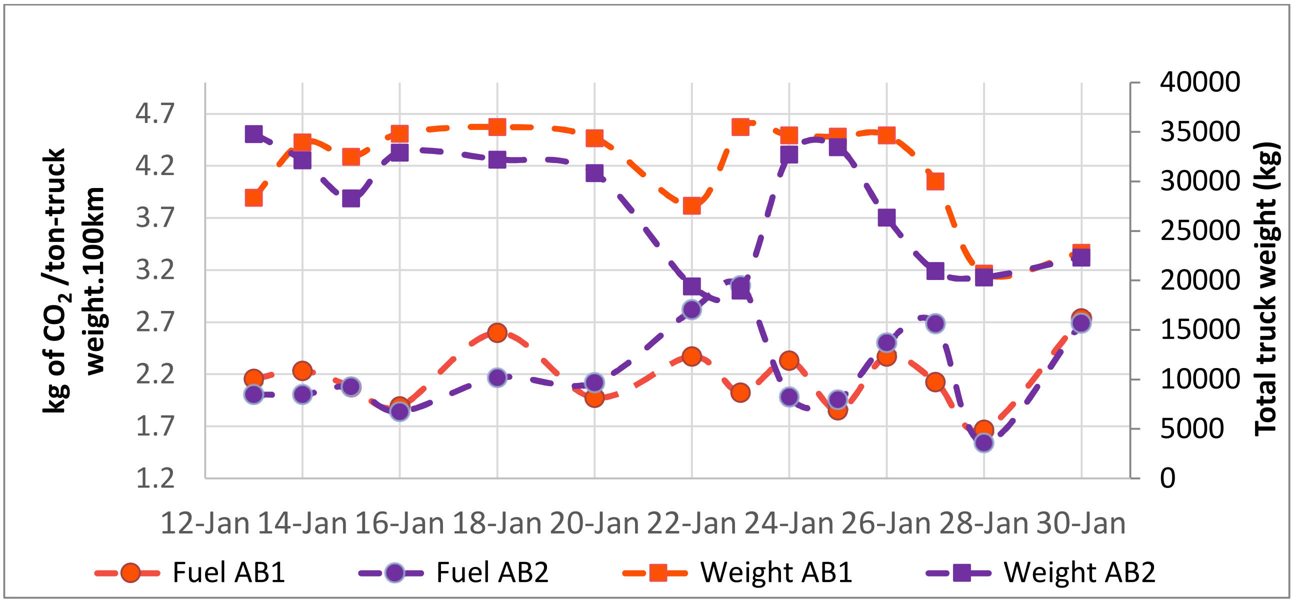
7.8. CO2 Greenhouse gas emission

There was no sensor for measuring the amount of CO_2 in the exhaust gases for the trucks used in the platooning project. Hence, we calculated the amount of emitted CO_2 by multiplying the factor of 3.1 and considering diesel fuel consumption. The factor of 3.1 assumes complete combustion of diesel fuel in the engine.

Figure 60(a) shows specific CO_2 emissions of the AB1 and AB2 trucks for Calgary to Edmonton trips. The behavior of the CO_2 production is similar to that of fuel consumption. All the parameters that increase the amount of specific fuel consumption, increase specific CO_2 emissions too. For the trips from Calgary to Edmonton CO_2 emission was in the range of 1.55 to 3 kg/(ton.100km).

Figure 60(b) shows specific CO_2 production of the AB1 and AB2 trucks for Edmonton to Calgary trips. For these trips CO_2 emission was in the range of 2.27 to 4.78 kg/(ton.100km). CO_2 emissions for Edmonton to Calgary trips are more than the trips from Calgary to Edmonton.

a) Calgary to Edmonton Trips



b) Edmonton to Calgary Trips

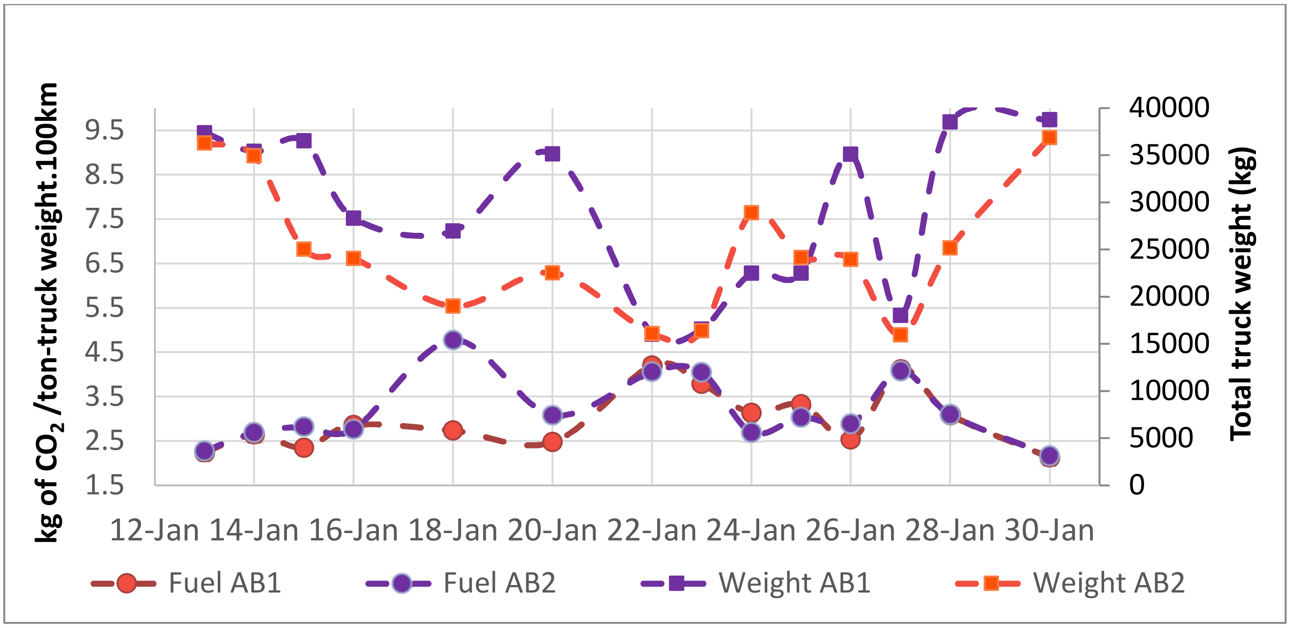


Figure 60: Specific CO2 emissions for the platooning trips

7.9. Instantaneous Engine Power Characteristic Effects on Specific Fuel Consumption

Analysis of cumulative fuel consumption behavior is based on the real-time fuel consumption measurements from the AIC fuel flow meter but review of instantaneous events in terms of seconds is based on the instantaneous fuel consumption graphs from ECU (SAE J1939). These graphs can be used along with other parameters to understand the performance of the truck in each road section.

In this part of the report, event-base analysis of the trips which had similar loads is discussed. For example, Figure 61 shows a 60-second section of the road when the platooning system is engaged. In this section of the road, AB2 has used more engine power to for this section of road. Table 14 shows the fuel consumption and engine-out NOx of AB1 and AB2 for this section of road. Values in the table show that the event in Figure 61 has not been a good performance for the platooning system. AB2 has consumed more fuel and caused more NOx emission than that of AB1.

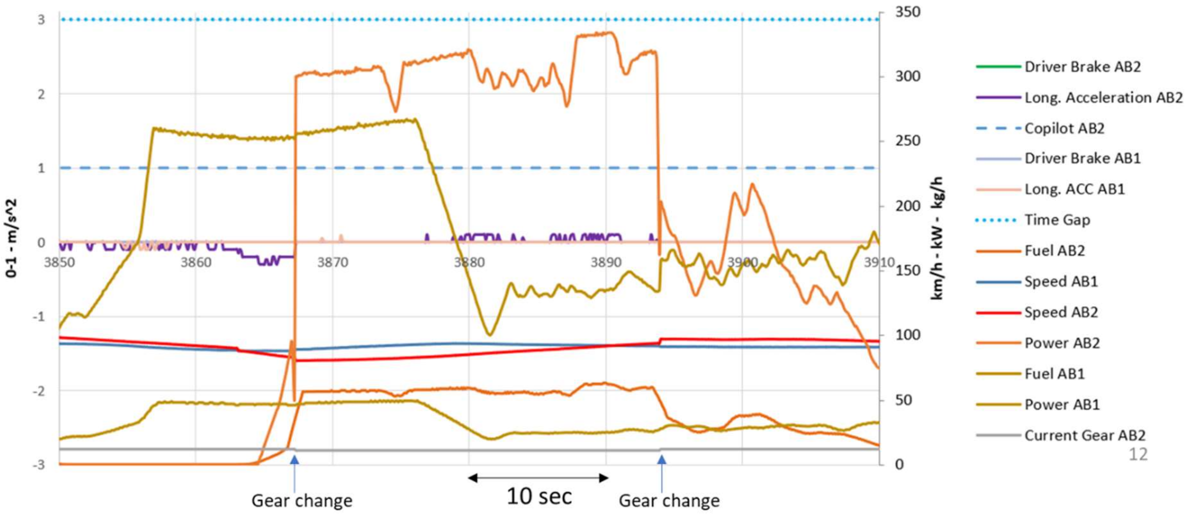


Figure 61: Instantaneous fuel consumption during a segment of the trip from Edmonton to Calgary on Jan 14

Table 14: Results for the selected section in the trip from Edmonton to Calgary on Jan 14

Parameter	AB1	AB2
Fuel Consumption (kg/ton.100km)	0.78	0.95
Engine NOx (gr/ton.100km)	22.9	27.2

Another section of trip is demonstrated in Figure 62. For this section of the road, the main characteristic is that there has been no acceleration and deceleration at all. The road section is smooth and without considerable grade down or up. Power oscillation of AB2 is slightly higher than AB1. Table 15 shows the fuel consumption and engine-out NOx of AB1 and AB2. AB2 consumed less fuel but generated more NOx compared to AB1 as shown in Figure 62.

Overall, the platooning system performs well with less power oscillations when there is a minimal grade change (i.e., a flat road) and no increase in fuel consumption of the follower truck is observed compared to the lead truck. But when there is a grade change or braking/acceleration by the lead truck, more power fluctuations are observed in the follower truck to maintain the platoon distance. During the control process by the follower truck, the engine power of the follower truck has more fluctuations compared to that of the lead truck. The extra transients in the follower truck often leads to more engine-out NOx emissions and more fuel consumption.

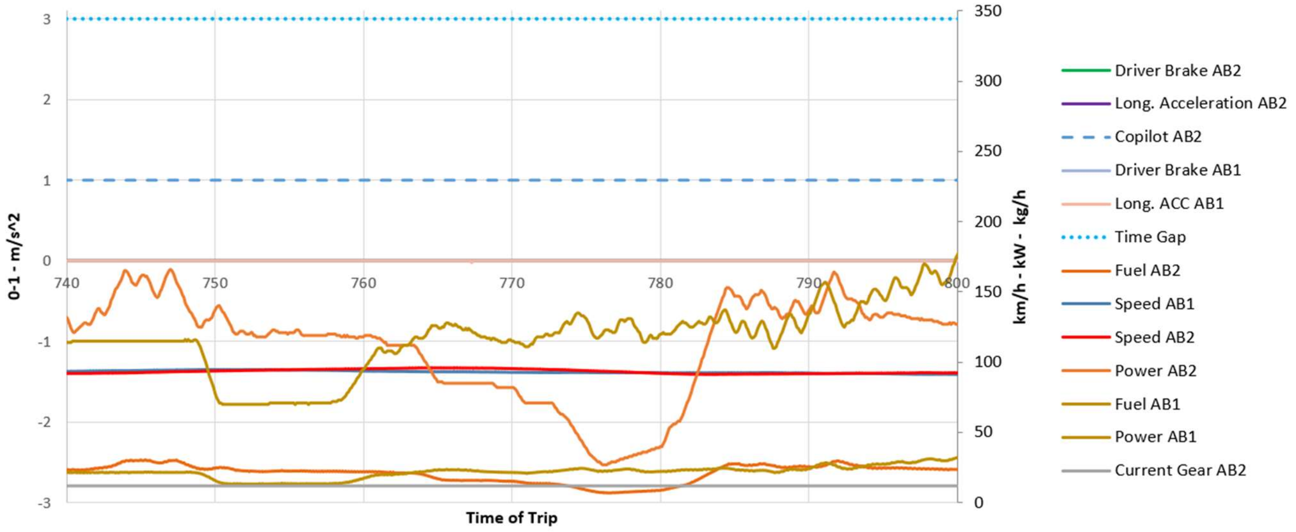


Figure 62: Instantaneous fuel consumption during a segment of the trip with no significant grade change from Edmonton to Calgary on Jan 14

Table 15: Results for the selected section in the trip from Edmonton to Calgary on Jan 14

Parameter	AB1	AB2
Fuel Consumption (kg/ton.100km)	0.7	0.6
Engine NOx (gr/ton.100km)	2.1	2.7

7.10. Disengagement and Re-engagement effects

Engine power curves for AB1 and AB2 and related parameters are shown for part of a road from Edmonton to Calgary in Figure 63. The main focus of the graph is to describe the reasons for power curve oscillation of the follower truck. As seen in the figure, the power curve of AB1 is not oscillating too much compared to the power curve of AB2 is showing a lot of fluctuations. Looking at the platooning situation (yellow dash line) and copilot situation (green dash line) it is observed that the platooning and copilot systems have engaged and disengaged frequently. The engagement and disengagement decisions are not taken by the driver and these decisions were made by the control system. This caused major step inputs to the powertrain control system of the AB2 truck. This could contribute to the increased fuel consumption for AB2.

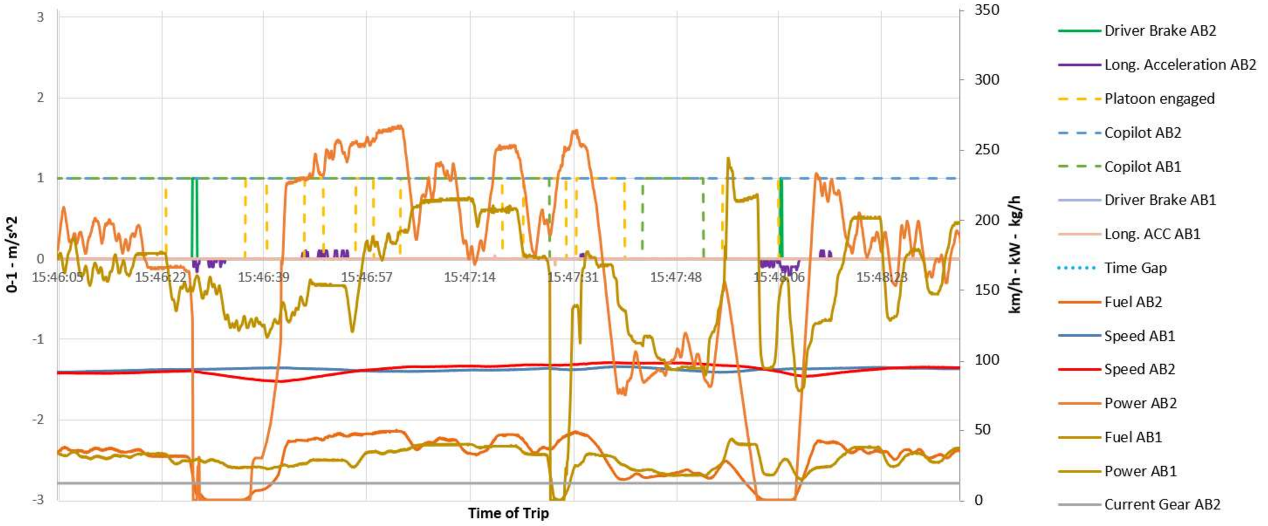


Figure 63: Example 1 - Segment-wise platooning performance signals along with the engine power oscillation

Another example is shown in Figure 64 for a section of the road as the evidence for AB1 and AB2 engine power curve fluctuation for a road section from Edmonton to Calgary. The main focus of showing this graph is to describe the reasons for power curve oscillation of the follower truck. Looking at the platooning situation (yellow dash line) and copilot situation (green dash line) it is visible that the platooning system engaged and disengaged frequently. Another similar example can be seen in Figure 65.

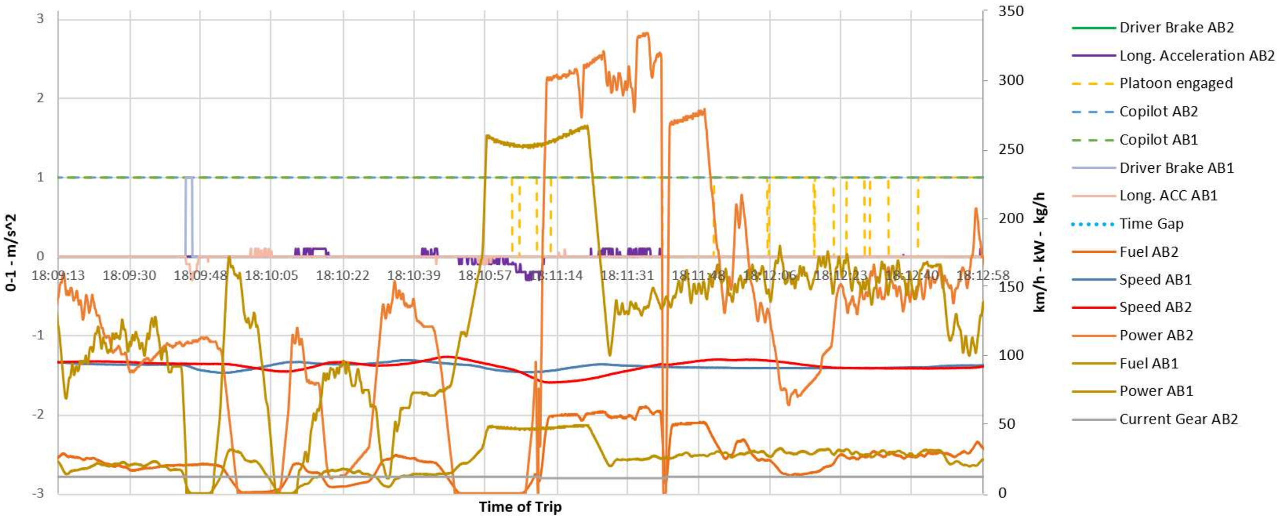


Figure 64: Example 2 - Segment-wise platooning performance signals along with the engine power oscillation

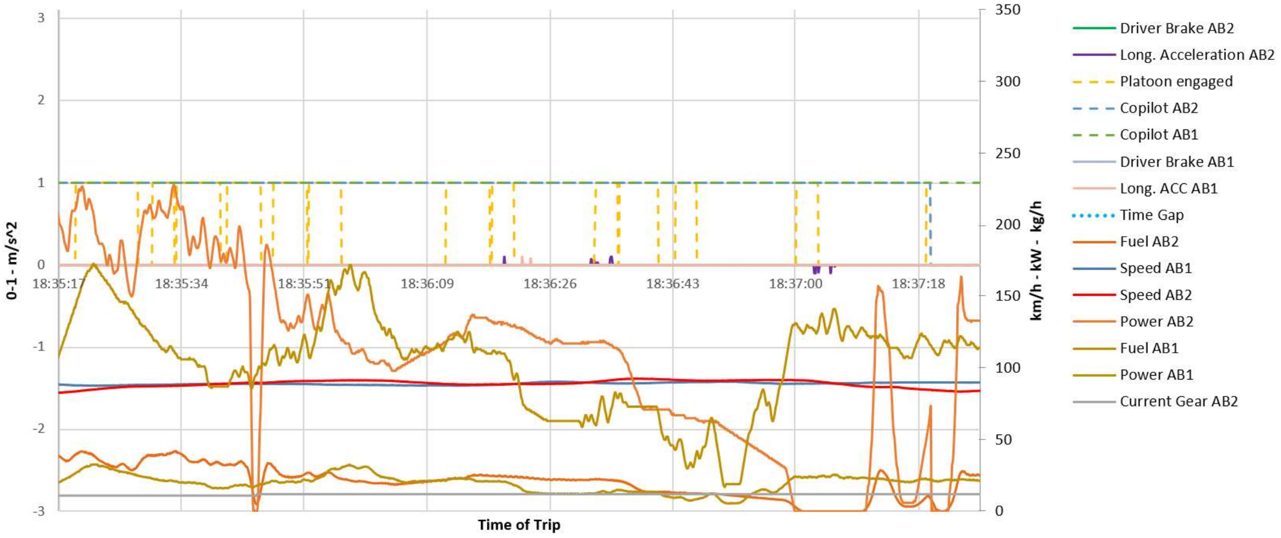


Figure 65: Example 3 - Segment-wise platooning performance signals along with the engine power oscillation

7.11. Potential effects on Engine Life

Event-based analysis of the Copilot control system for a section of the road is shown in Figure 66. The main focus of the graph is to highlight power oscillations of the follower truck when the platooning system is disengaged but copilot is still engaged. For the section after disengagement of platooning system (red arrow) the copilot system remained engaged (blue and green dash lines). The follower truck's engine shows a lot of power oscillations. These large power oscillations are not desired for the engine's life, particularly when it is repeated frequently. This also adversely affects engine-out NOx emissions depending on engine calibration, and how fast and robustly exhaust gas recirculation (EGR) and air charge control is performed during the engine transients.

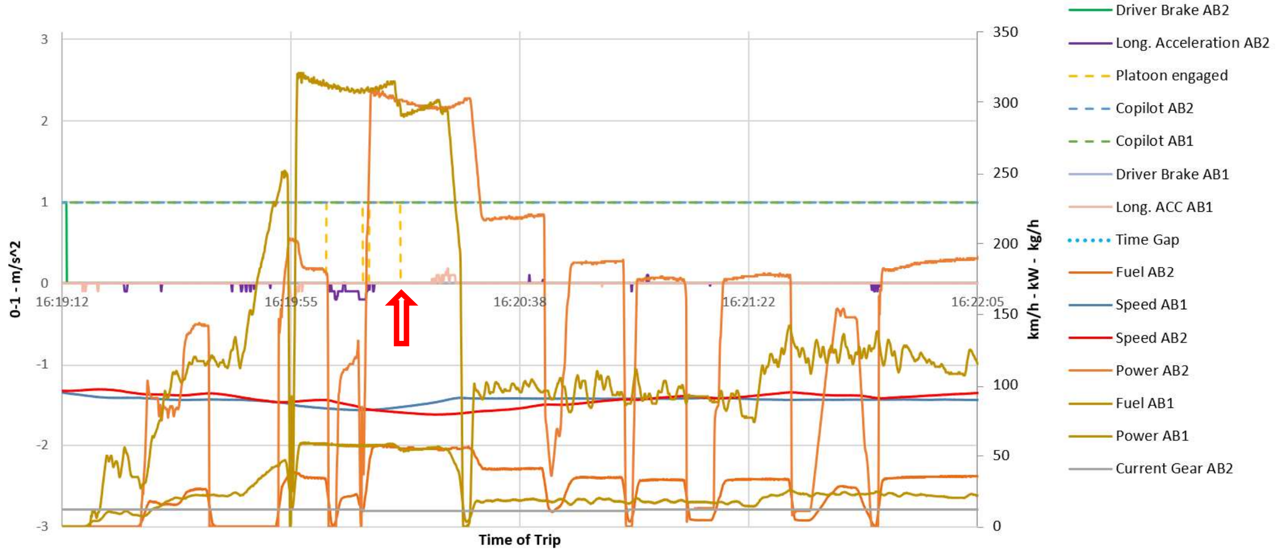


Figure 66: Event-based Copilot performance and its effect on the engine power oscillation

8. Vehicle and Traffic Interaction Assessment

The on-road trial using on-board sensors (i.e., vehicular cameras, radars and partially automated driving systems) aimed to investigate the performance of vehicle dynamic and traffic interactions in typical cooperative truck platooning system (CTPS) scenarios. This includes maneuvering patterns of truck platooning, headway (the distance between vehicles), other cut-in and cut-out vehicles, traffic flow, and travel time. In this project, we studied the impacts on traffic flow due to partially automated CTPS, considering variables such as headway in a platoon, platoon speed and platoon length, in addition to understanding the performance of truck operations in CTPS conditions. Furthermore, we assessed the operational impacts and the key factors of influence in the operational design domain.

The on-road trial conducted in naturalistic driving situations involved abundant traffic scenarios, with the lead truck and following truck operating at constant speeds or dynamic speeds when interacting with surrounding traffic vehicles. During the on-road trials, attention has been given to the typical seven scenarios that occurred most during the platooning. These scenarios can be seen in Figure 67 and are described below:

1) Benchmark truck platoons. This is the most common scenario, and it simply involves regular platoon operations without any interaction with surrounding vehicles.

2) Follow random traffic vehicles. This scenario occurs when a vehicle changes lanes and drives in front of the leading truck while platooning.

3) Traffic vehicles cut-in. This scenario takes place when a vehicle changes lanes and drives between both platooning trucks.

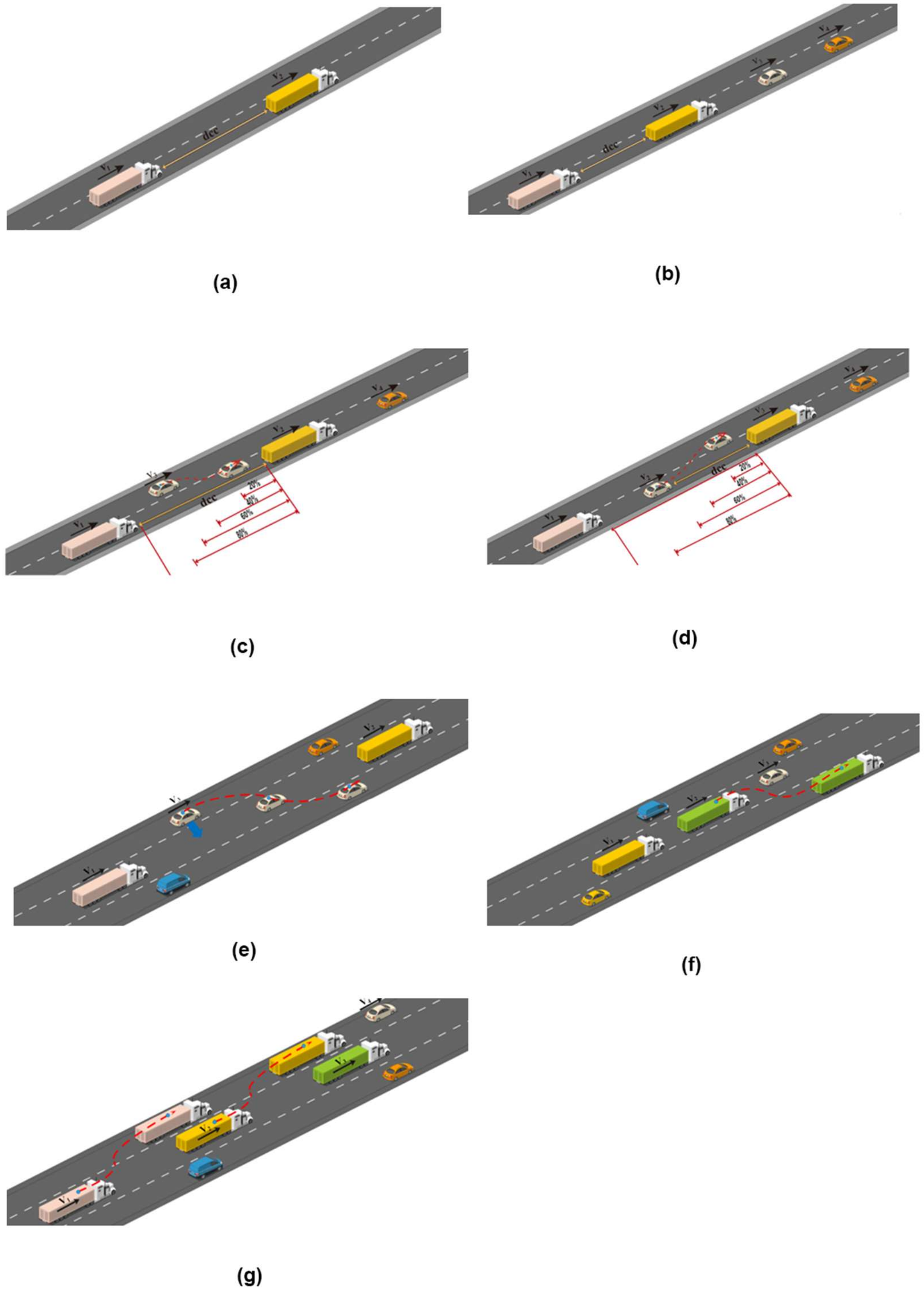
4) Traffic vehicles cutting-out. This scenario occurs right after scenario 3, when the cut-in vehicles decide to cut out, i.e. changes to a different lane, so the platoon can re-engage and operate as normal.

5) Traffic vehicles cross over. This occurs when a vehicle cuts in between both trucks rapidly to change to a different lane different from the lane where the trucks are driving.

6) Revealed traffic vehicle. This scenario happens when the leading trucks changes lanes and another vehicle is revealed in front of the following truck.

7) Platoon lane change. This scenario happens when both trucks change lanes while platooning.

Different metrics and possible causes for the various responses of the platoon to different scenarios will be analyzed and discussed. In this section, we will attempt to explain the possible causes for the different responses in which the platoon reacted to various circumstances during the trials. This is important given the lessons that can be learned and used for future implementations of Cooperative Truck Platooning Systems, in terms of road safety, efficiency, fuel consumption, and others. For this purpose, a manual inspection algorithm was developed, allowing careful analysis of the different scenarios and responses to all interactions. Each metric will be explained in detail with their respective implications. Finally, findings and recommendations will be discussed in the conclusions.



(a) (b) (c) (d) (e) (f) (g)

Figure 67. Different traffic interaction scenarios: a) benchmark truck platoons, b) follow random traffic vehicles, c) traffic vehicles cut-in, d) traffic vehicles cutting-out, e) traffic vehicles cross over, f) revealed traffic vehicle and g) platoon lane change

8.1. Methodology

The methodology for this section of the project entails aspects from the data collection stage to the data analysis of all matters regarding platoon behavior and interaction with surrounding traffic along AB Highway 2 between Calgary and Edmonton. Twenty-one trial runs were completed, covering a total of 23,400 km of traveled road, with nine different drivers. Different times of day and weather conditions were observed during these trials, which allows to account for different situations that might arise during the Albertan Winter.

8.1.1 Data Collection

Data collection took place for the duration of the on-road trials from January 12 to January 30, 2022. Two 2020 Peterbilt 579 trucks were equipped with a co-pilot system that allowed for maintaining a platoon of a headway setpoints ranging from 3 to 5 seconds. The route began in Calgary, driving up to Edmonton on AB Highway 2, and driving back to Calgary again using Highway 2. The extent of this route is about 300km each way and can be seen in Figure 68. This highway consists predominantly of four lanes, divided, with low grades and long straight sections.

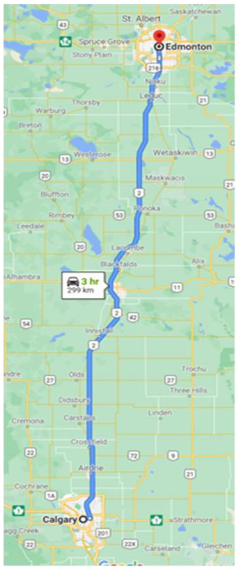


Figure 68. AB Highway 2 between Calgary and Edmonton.

During the trials, the platoon was engaged usually for one to three hours. This provided the opportunity to make substantial analysis regarding the platoon interactions with surrounding vehicles and the behavior of the platoon when facing common situations along Highway 2.

Conditions for data collection were classified according to road type (e.g. straight, curve, uphill, downhill, on-ramp, off-ramp), road condition (e.g. bare dry, bare wet, shoulder ice/snow, partly covered snow), weather condition (sunny, partly sunny, passing clouds, overcast, mostly cloudy, clear, light snow), so as to consider external factors that could influence the outcome of the trials and traffic behavior.

The types of data collected during the on-road trials can be divided into two groups: OBD II (On-board diagnostics) Data and Video data. OBD data provides important information, such as vehicle speed and whether it has engaged in platooning, turned on the co-pilot system and others. Video data for both trucks was collected from inside the driver's cabin and from the windshield with a view of the road ahead. Table 16 shows the periods of platoon engagement and how much video data of high quality was retrieved during the trials. Over 585 videos from the lead truck and 570 videos from the follower truck were retrieved and analyzed, each one consisting of approximately 20 minutes of footage, gathered in over 34 hours of platooning. The overall video quality was low during the first few days of the trial due to technical malfunctions with the selected camera, freezing midway during the trips. This issue was addressed and fixed shortly after the trials started, resulting in high quality video data for most of the trials, accounting for about 80% of all the videos. Days without platooning due to truck maintenance are identified as NA. The trip number corresponds to days where more than one trip was made, with Trip 1 being a trip from Calgary to Edmonton and Trip 2 being a trip from Edmonton to Calgary.

Table 16. Video data retrieved during on-road trials.

Date	Trip	Real time platooning duration (hr)	Free-of-technical issues videos duration while platooning (hr)	Percentage of available videos for processing %
Jan 12	1	1:00:30	0:32:11	53.20%
Jan 13	1	0:59:28	0:59:21	100.00%
Jan 13	2	1:07:45	0:00:00	0.00%
Jan 14	1	1:23:31	0:00:00	0.00%
Jan 14	2	1:17:53	0:00:00	0.00%
Jan 14	3	0:00:00	0:00:00	0.00%
Jan 14	4	0:00:00	0:00:00	0.00%
Jan 15	1	1:56:06	1:56:52	100.00%
Jan 15	2	1:39:21	0:00:00	0.00%

Jan 16	1	1:27:58	1:28:58	100.00%
Jan 16	2	0:53:02	0:53:22	100.00%
Jan 17	1	0:00:00	0:00:00	0.00%
Jan 17	2	0:00:00	0:00:00	0.00%
Jan 18	1	0:03:55	0:03:56	100.00%
Jan 18	2	0:33:30	0:35:25	100.00%
Jan 19	0	NA	NA	NA
Jan 20	1	0:58:31	0:51:06	87.33%
Jan 20	2	0:50:18	0:00:00	0.00%
Jan 21	0	NA	NA	NA
Jan 22	1	1:53:27	1:56:22	100.00%
Jan 22	2	1:40:20	0:00:00	0.00%
Jan 23	1	1:56:15	1:57:00	100.00%
Jan 23	2	0:55:18	0:55:51	100.00%
Jan 24	1	0:03:01	0:30:54	100.00%
Jan 24	2	0:02:16	0:10:15	100.00%
Jan 25	1	1:09:20	1:10:04	100.00%

Jan 25	2	2:00:08	2:05:23	100.00%
Jan 26	1	1:25:12	1:26:17	100.00%
Jan 26	2	0:41:03	0:42:03	100.00%
Jan 27	1	1:53:12	1:56:54	100.00%
Jan 27	2	1:29:19	1:41:08	100.00%
Jan 28	1	2:05:30	2:07:22	100.00%
Jan 28	2	0:00:00	0:00:00	0.00%
Jan 29	0	NA	NA	NA
Jan 30	1	2:08:55	2:09:47	100.00%
Jan 30	2	1:10:40	1:12:01	100.00%

8.1.1.1 Camera Installation

One traffic camera was installed per truck, on the windshield, in order to assess traffic interactions and platoon behavior. For this section of the project, only the road camera was analyzed as it directly pertains to the operational aspects of the project and helps identify the different scenarios of traffic interaction. The camera chosen for the roadside capture was a GoPro Hero 9 Black with favorable features, such as 5K video capability, 1.4'' color display with live preview, HyperSmooth 3.0 in-camera horizon leveling, and others. Its only weak points are night-time performance and some freezing problems after certain periods of time, which were fixed by constantly monitoring the video performance live during the trials, and correcting or restarting the camera when necessary. However, the platoon was rarely engaged during dark conditions, so most of the platooning video data could be analyzed without issues. The camera offered a wide angle, as to permit viewing the neighboring lanes, and surrounding traffic. The camera was attached to the windshield with a suction cup, and a USB Type-C cable was used to connect the camera directly to the DAQ system without the need of batteries for power or SD cards for storage. Dewesoft was used to record the videos during the trials. Figure 69 shows a preview of the road camera view from which operational analysis could be made.

Figure 69. A sample of the images captured from the road camera installed in the follower truck.

8.1.1.2. Type of Data Recorded

Data was collected from multiple sensory sources using the DAQ system, such as GPS, speed sensor, temperature sensor, camera, etc. Platooning parameters such as time gap, lead speed and follower speed were also recorded. For the purpose of traffic interaction analysis, we will only use part of the relevant DAQ data and the video data. The specification of data used for traffic interaction analysis is shown in Table 17.

Table 17. Data specification

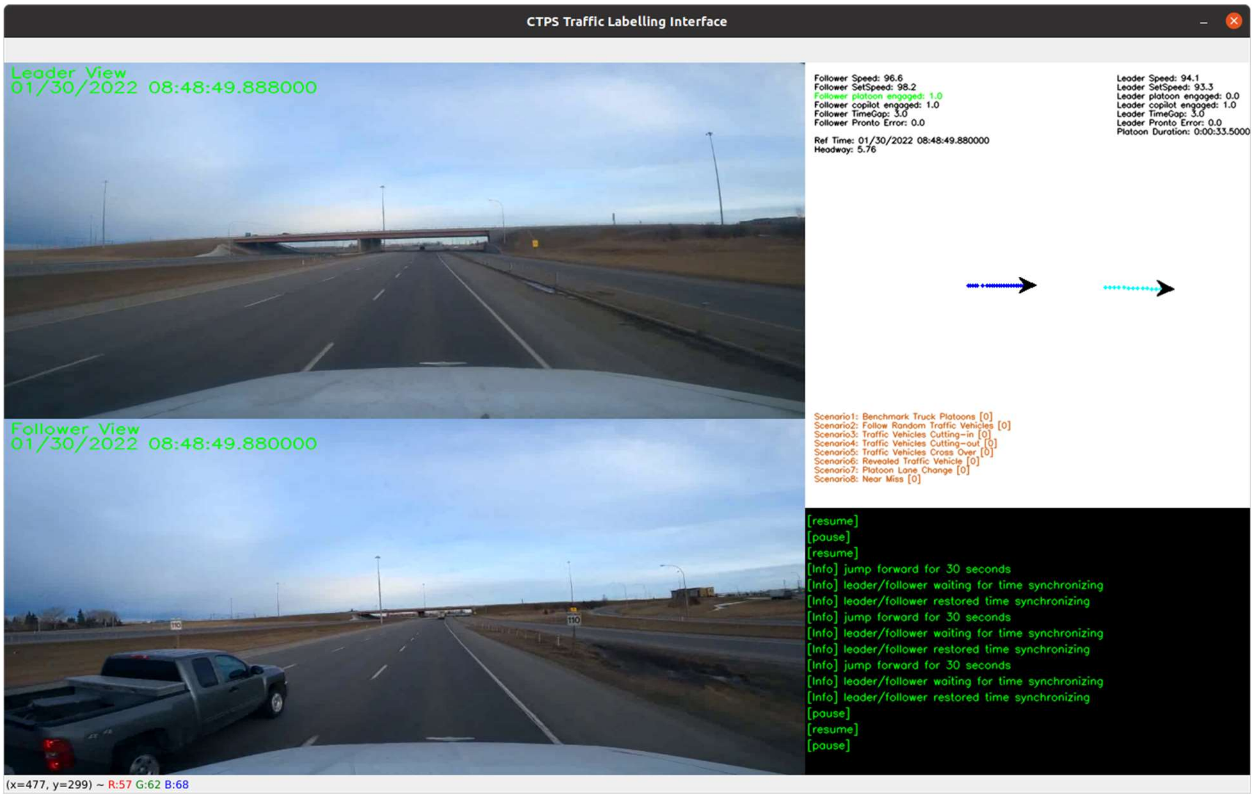
Data Type	Description	Format	Sample Rate (Hz)	Data Source
Time	Timestamp from GPS clock	year, month, day, hour, minute, second	10	Lead and follower trucks
Latitude/longitude	GPS coordinate	WGS84	10	Lead and follower trucks

Yaw	Truck orientation	degree	10	Lead and follower trucks
Lead Speed	Truck speed	km/h	10	Lead truck
Follower Speed	Truck speed	km/h	10	Follower truck
Platoon Engaged	Platoon engagement indicator	0 or 1	10	Follower truck
Copilot Engaged	Copilot engagement indicator	0 or 1	10	Follower truck
Time Gap	Pre-configured time gap between lead and follower trucks	second	10	Follower truck
Follower Set Speed	Pre-configured platooning speed	mph	10	Follower truck
Lead Video	Video recorded using the GoPro camera	.avi	30	Lead truck
Follower Video	Video recorded using the GoPro camera	.avi	30	Follower truck

8.1.2. Analysis Method

8.1.2.1 Scenario Labeling

A Python-based graphical interface has been developed for human analysts to label the collected data (see Figure 70 below). The interface presents the camera views for the lead truck and the follower truck at the same time, along with the speed, headway, platooning status, time, GPS position and trajectories for the analyst. The analyst watched the video and determined whether an interaction occurred by pressing the corresponding digit key, and once an interaction is labeled, the timestamp, speeds, headway, platooning status, and the corresponding time for each video will be recorded for detailed analysis.



```
Follower Speed: 96.6
Follower SetSpeed: 98.2
Follower platoon engaged: 1.0
Follower copilot engaged: 1.0
Follower TimeGap: 3.0
Follower Pronto Error: 0.0

Ref Time: 01/30/2022 08:48:49.880000
Headway: 5.76
```

```
Leader Speed: 94.1
Leader SetSpeed: 93.3
Leader platoon engaged: 0.0
Leader copilot engaged: 1.0
Leader TimeGap: 3.0
Leader Pronto Error: 0.0
Platoon Duration: 0:00:33.5000
```

```
Scenario1: Benchmark Truck Platoons [0]
Scenario2: Follow Random Traffic Vehicles [0]
Scenario3: Traffic Vehicles Cutting-in [0]
Scenario4: Traffic Vehicles Cutting-out [0]
Scenario5: Traffic Vehicles Cross Over [0]
Scenario6: Revealed Traffic Vehicle [0]
Scenario7: Platoon Lane Change [0]
Scenario8: Near Miss [0]
```

```
[resume]
[pause]
[resume]
[Info] jump forward for 30 seconds
[Info] leader/follower waiting for time synchronizing
[Info] leader/follower restored time synchronizing
[Info] jump forward for 30 seconds
[Info] leader/follower waiting for time synchronizing
[Info] leader/follower restored time synchronizing
[Info] jump forward for 30 seconds
[Info] leader/follower waiting for time synchronizing
[Info] leader/follower restored time synchronizing
[pause]
[resume]
[pause]
```

Figure 70. Scenario Classification Interface

A total of eight scenario types were characterized in the interface. The first seven are pre-defined traffic scenarios: 1) benchmark truck platoons, 2) follow random traffic, 3) traffic vehicle cut-in, 4) traffic vehicle cutting-out, 5) traffic vehicles cross-over, 6) revealed traffic vehicle, and 7) platoon lane change. The additional one is near miss scenario, added to characterize unplanned events with the potential to cause an incident, which is not part a traffic scenario, but we use the same method to label near misses in the interface for convenience.

One challenge of the interface implementation was to address the time misalignment of the recorded data. This was due to the fact that the data recording was managed by the driver in each of the trucks in a decentralized way, although the GPS clocks are used to synchronize the time for each DAQ device, and the sample rate for each recording sensor is constant (30Hz for the camera and 10 Hz for DAQ devices), the starting times and the durations of each data sequence (each video recording) are arbitrary (see Figure 71). For the purpose of labeling the eight traffic scenarios, the platooning status and the camera views of both trucks need to be presented with as little time difference as possible. This was accomplished by a scheduling algorithm (see Figure 72), assuming that the timestamp provided by the GPS clock was accurate.

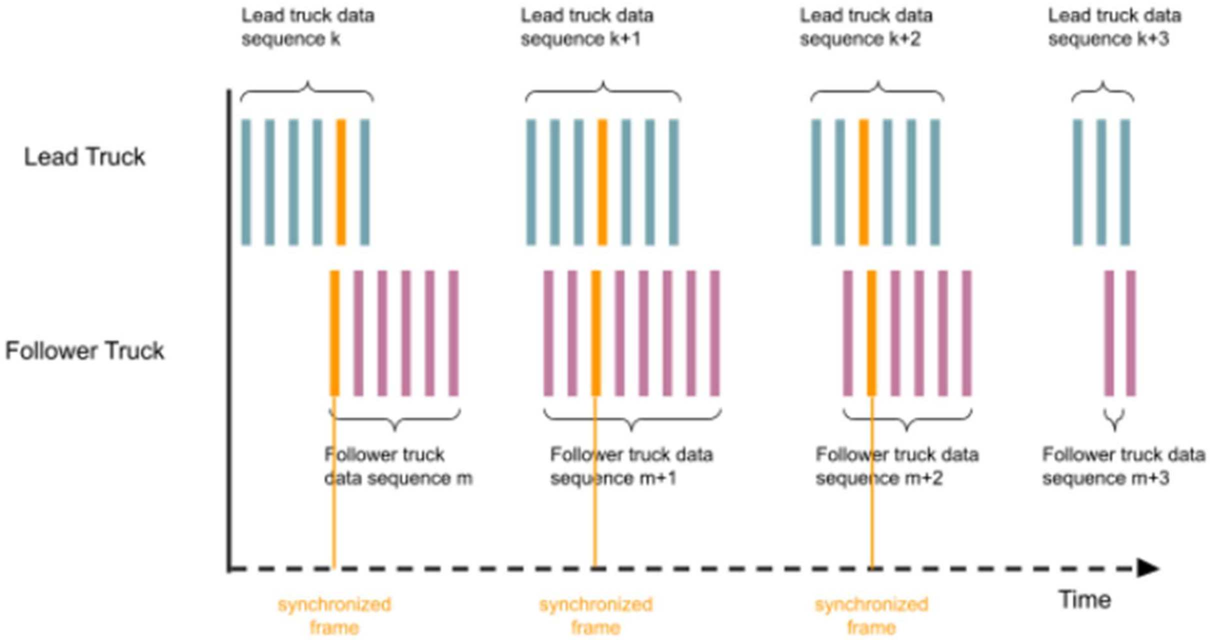


Figure 71. For data recording both trucks have arbitrary starting time and duration for the recorded data sequences, and that causes misalignment of the timestamps even if the GPS clocks for both trucks are assumed to be accurate. For scenario labeling the data frames for both trucks need to be presented in a synchronized manner with time difference between the two trucks as small as possible, as shown in the yellow synchronized frames as examples.

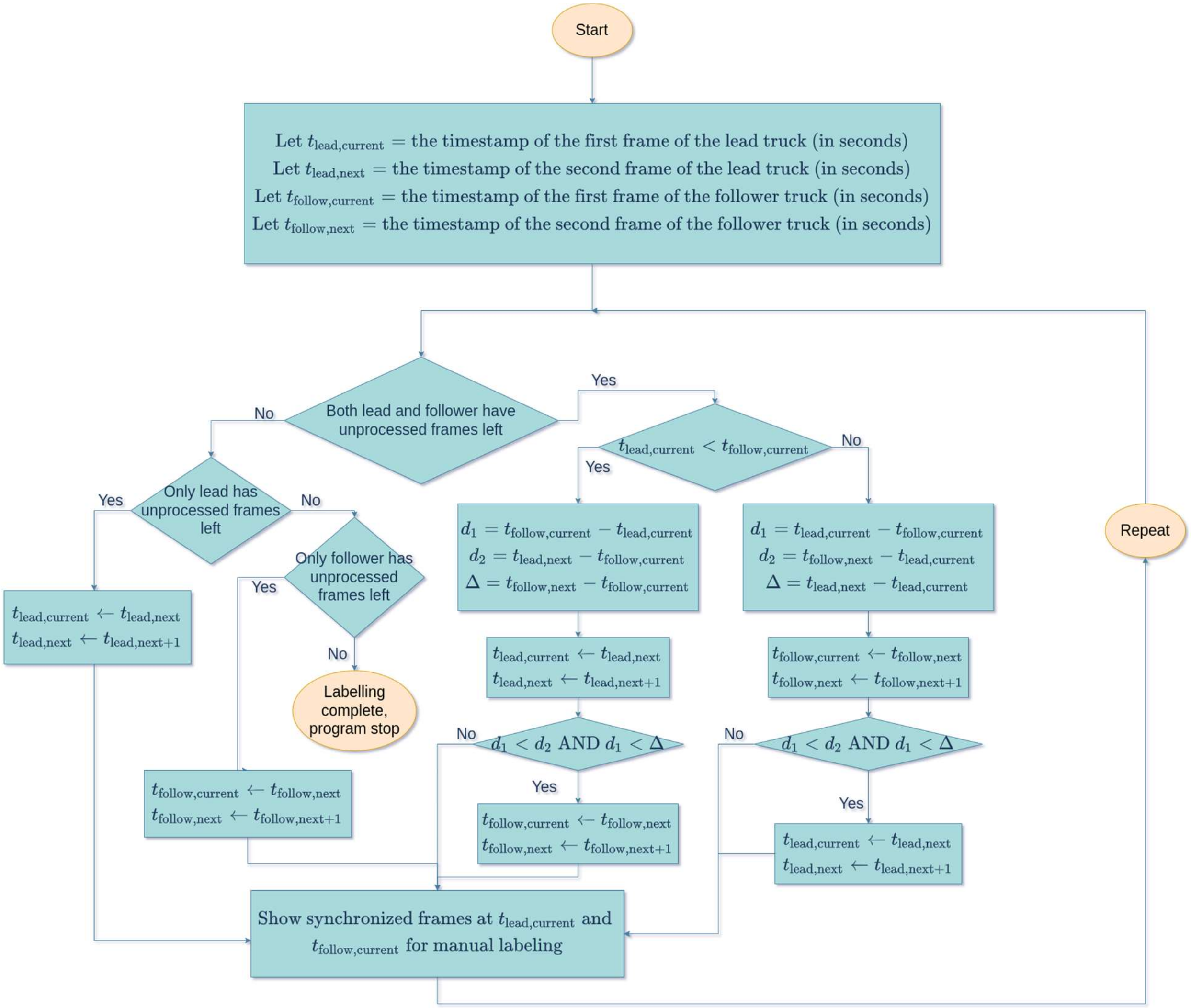


Figure 72. Scheduling algorithm. The algorithm will make sure that when presenting a synchronized frame to the user, the lead truck and the follower truck data will be at approximately the same time of recording, with time difference (d1) minimized, assuming that the GPS clocks for the two trucks are accurate.

We also attempted to develop a computer vision (CV) based algorithm to process the collected data and label the occurrences of each scenario automatically without human intervention. Ideally completely replacing the manual labeling procedure to save human labor. However, due to time constraints of this project we could not finish the development of the CV algorithm. The algorithm used FCOS3D (a deep learning-based 3D object detector. Wang, Tai, et al. 2021.) to recognize and localize the traffic vehicle from a single image of the video data (see Figure 73), and then the detected vehicles are tracked for consecutive image frames based on their visual appearances on the image and the tracking is accomplished using Hungarian algorithm (a classical algorithm to solve linear assignment problem). Combining the tracking results with GPS data, we can get the traffic vehicle trajectories together with their speed estimations, see Figure 74 for a sample result. More study and experiments are needed to classify the occurrence of each scenario based on the traffic vehicle trajectories and the lane boundaries. For example, to determine a traffic vehicle's cut-in, the algorithm needs to check if the traffic vehicle trajectory has crossing the lane ahead of the follower truck.

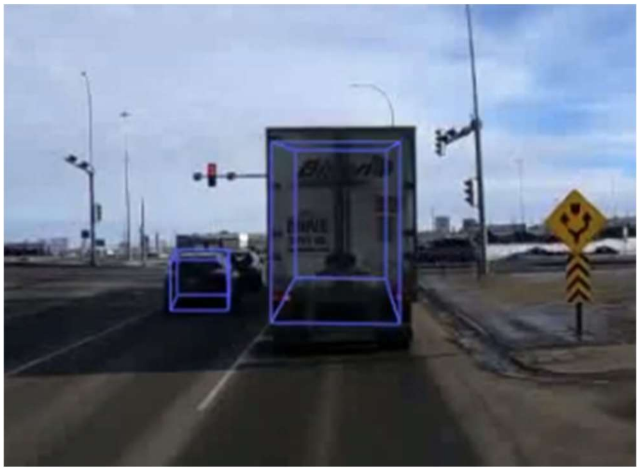


Figure 73. 3D bounding box detection with FCOS3D (a deep learning-based detection model, Wang, Tai, et al. 2021)

Figure 74. Vehicle tracking and speed estimation. The cyan color represents the ego truck's GPS trajectory, and gray, black, red and purple color are the traffic vehicle's trajectories with their IDs (assigned sequentially based on the order of detection) and the speed estimation (in km/h).

Since the project timeline is limited, despite the effort we made, the CV algorithm still requires extensive development and testing to guarantee a reliable result before applying to the traffic analysis. Therefore, we decided to use manual labeling. A comparison between the manual labeling and computer vision-based algorithm is shown in Table 18.

Table 18. Comparison between manual labeling computer vision-based algorithm labeling

	Manual Labeling	Computer Vision Algorithm
Pros	• More accurate classification • Relatively easy to implement labeling interface • Better interpretability	• Less human labor required • Capable of estimating traffic vehicle trajectory and speed from video • Learnable • Consistency
Cons	• Difficult to estimate traffic vehicle trajectory from eye-observation • Human ambiguity exist • More human labor required • High time consumption for labeling	• Less accurate due to sensor noise, light variability and capability of Deep Learning models • Challenging to develop the algorithm • Traffic vehicle detection is limited by maximum detection distance (for FCOS3D the max range is around 60 meters, could be improved by using other detectors)

8.2. Data Analysis

To investigate the behavior of the CTPS during platooning, the seven scenarios have been identified using the manual classification method. This included recording the exact time and date of the events, the road and weather condition, the initial position of other traffic vehicle that is cutting in or crossing over between the two trucks, and the speed of both trucks.

The first two scenarios — benchmark truck platoon and following random traffic vehicles — have been eliminated in the analysis stage later, as they are not responsible for the change done in the behavior of the follower truck (the platoon) in comparison to the other five scenarios. They have been recorded to examine the ability of the lead truck to follow random traffic during platooning, in addition to observing if there are any emergency speed reductions for the lead truck due to a close cutting in front of the lead truck or near misses.

The other five types of interactions were classified in order to understand the platoon response during every type of these scenarios. Table 19 shows the number of interactions recorded during platooning for scenarios 3–7. Scenarios 3 and 4 have a statistically valid sample size, so greater attention has been given to study the behavior of the platoon during these two scenarios in different headway conditions, while scenarios 5-7 can be assessed only on an exploratory basis due to the smaller sample size. The purpose of studying scenario 7 aimed to investigate the behavior of the platooning system during lane changing. However due to CTPS operation platoon lane changes were conducted in a disengaged state and only one lane change event was recorded.

Table 19. Number of Interactions

Type of Interaction	Number
Scenario 3 - Traffic vehicle cutting in	52
Scenario 4 - Traffic vehicle cutting out	24
Scenario 5 - Traffic vehicle cross-over	11
Scenario 6 - Revealed traffic vehicle	6
Scenario 7 - Platoon lane change	1
Total	94

The first step after the interaction had been classified was to calculate the frequency of every interaction for the three different gap distances between the two trucks during platooning. In regard to the speed of the traffic for the different scenarios relative to the speed of the trucks, it was observed that almost all interactions occurred when the traffic vehicle was driving at the same or a higher speed than the trucks. Only one exception for a cut-out in which the traffic vehicle changed lanes at a lower speed. Figure 74 describes the frequency for each of the scenarios at the various headway distances. It shows that for scenario 3 (Cut-Ins) a higher frequency (around five times per hour) occurred during the 5 sec headway, and a lower rate occurred in the 4 seconds gap while the lowest frequency rate occurred during the shortest gap 3 sec between the two trucks. It was observed from the videos that the traffic vehicles prefer to switch lanes to the truck lane after overtaking the lead truck especially when the distance between the two trucks is short. It also shows that the cut-in frequency linearly increased as the headway distance increased, since traffic vehicles found a bigger gap between trucks to perform this maneuver.

Figure 75 also shows that there is a big difference in the frequency rate of cuts-outs during the 5 seconds gap in comparison to the other two headways. The larger space between the trucks allows traffic vehicles to perform these maneuvers with more confidence.

The other three scenarios have low occurrences, however there are still a higher rates at the 3 seconds gap. Given the smaller sample size for these scenarios with low rates, it was not possible to determine causes for these responses.

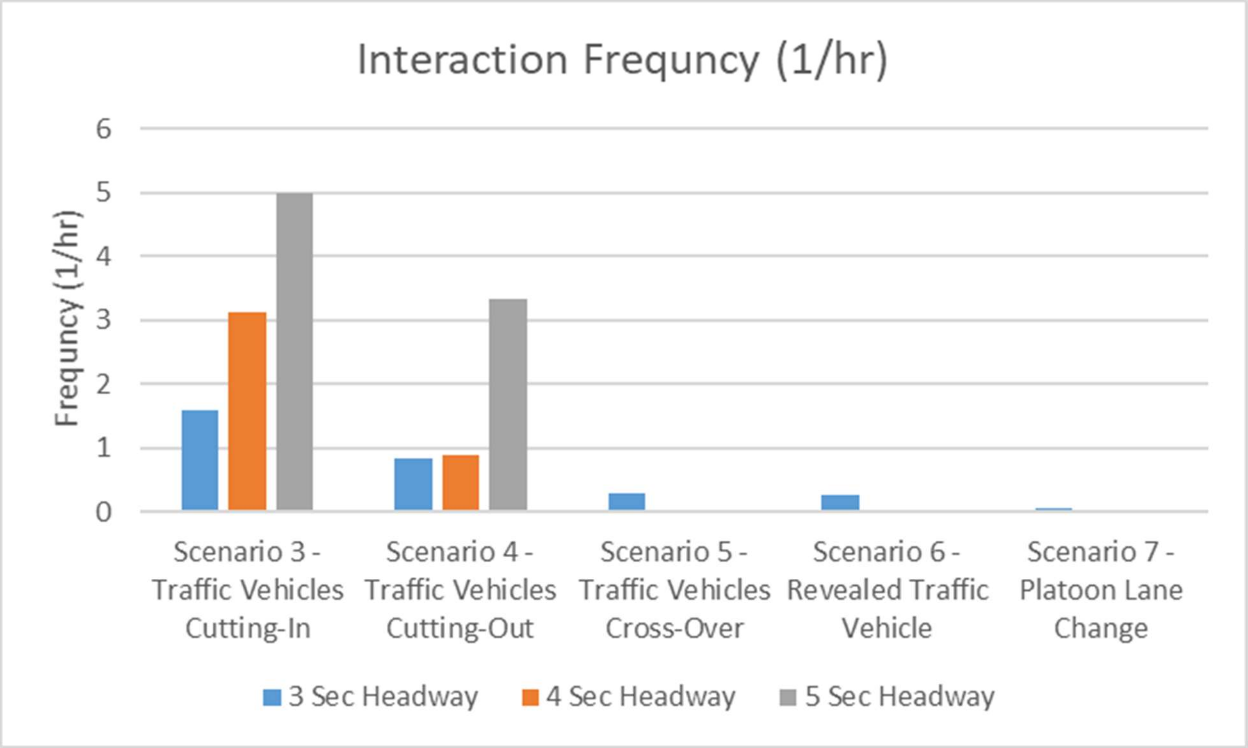


Figure 75. CTPS Interactions Frequencies

8.2.1. Investigating the Cut-in Interactions

To characterize the traffic interactions, we studied two variables in this section below, namely the cut-in duration (X) and the maximum speed difference between the lead and the follower trucks during the cut-in (Y). The scatter plot is shown in Figure 75, where the horizontal axis represents the predictor variable, and the vertical axis represents the response variable. We can see that the two variables are approximately following a linear correlation, so a linear regression model was applied, and the resulting model parameters are listed in Table 20. After model fitting, there is a positive correlation between the predictor variables and the response variable with the Pearson correlation coefficient of 0.6244 (ranging from -1 to 1, -1 means strong negative correlation, 1 means strong positive correlation, and zero means no correlation), and with a coefficient of determination of 0.3899 (indicates that 38.99% of variation in the response variable explained by the predictor variable). The linear regression model is then defined by:

$$Y = 0.2088\,X \;+\; 2.7584$$

From the model, we can see that the maximum speed difference between lead and follower trucks depends on the cut-in duration of the traffic vehicle (i.e., the time the traffic vehicle spends between the platoon trucks), and their relation can be estimated based on the linear regression model above. The longer the cut-in takes, the larger the speed difference becomes due to the fact that the follower truck needs to reduce its speed, and this effect becomes more obvious when the cutt-in duration is large, as shown in Figure 76.

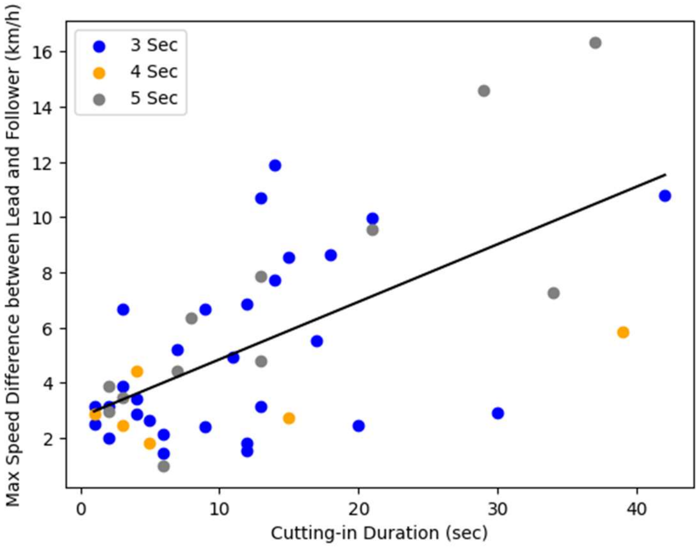


Figure 76. Linear regression.

Table 20. Parameters of the linear regression model

Slope	Intercept	The Pearson correlation coefficient	Coefficient of determination
0.2088	2.7584	0.6244	0.3899

The linear regression model assumes that the residuals (the difference between the actual response variable and the predicted response variable) are normally distributed with a zero mean. To verify whether the assumption holds, we plot the residual histogram, the estimated kernel density curve (in blue) and the corresponding normal curve of residuals (in orange) overlay in Figure 77. We can see that the estimated kernel density curve is very close to the zero-mean normal distribution curve, and that indicates that the linear regression model assumption is met.

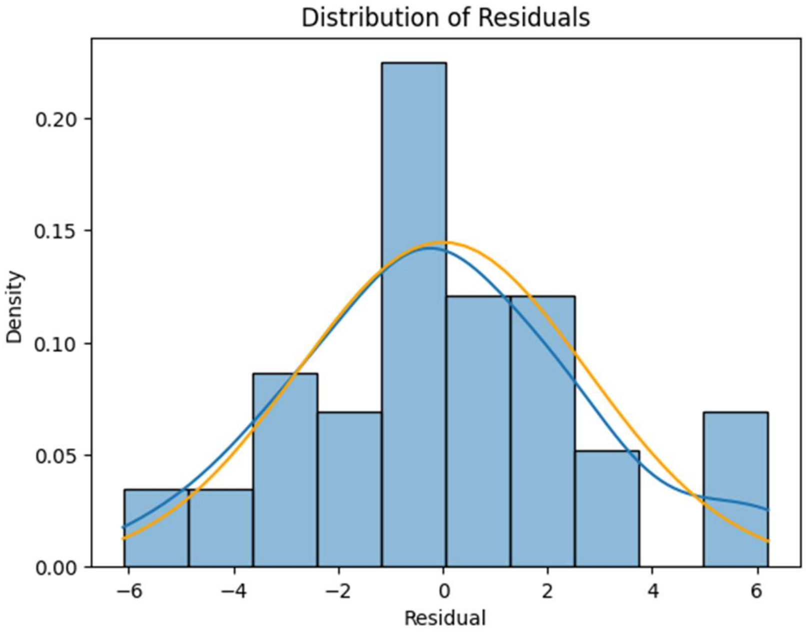


Figure 77. Linear regression residual distribution. The blue bar chart shows the density histogram of the residuals, and the estimated kernel density curve is used to smooth the distribution and compared with the corresponding normal curve in orange color. The closer the two curves overlap the better the normal residual assumption holds.

The distribution of cut-in duration for 3, 4 and 5 seconds headway are shown in Figure 78, with the bar heights representing the percentages of samples. The kernel density estimation is also applied to the histograms and generated smooth curves. The 3 seconds headway group in Figure 12 are approximately bell-shaped with the mean value at 11.24 seconds, however for both the 4 and 5 seconds groups, there exist second peaks in the histograms at around the 30 to 40 seconds range. This is likely due to the small sample size bias, and the smoothed kernel density curves do not show obvious peaks for all three groups. The detailed statistics for the distribution are presented in Table 21 for reference.

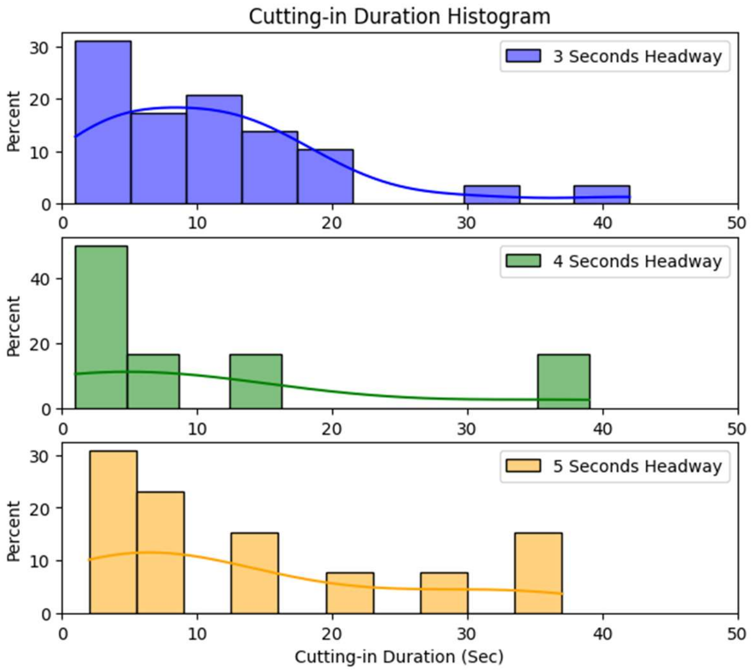


Figure 78. Histograms of cut-in duration for 3, 4 and 5 seconds headway.

Table 21. Statistics of cut-in durations for 3, 4 and 5 seconds headway.

	Mean	Standard Deviation	Maximum	Minimum	Sample Size
3 Seconds Headway	11.24	9.12	42	1	29
4 Seconds Headway	11.16	11.48	39	1	6
5 Seconds Headway	13.76	12.45	37	2	13

Given the statistics in Table 21, we conduct a one-way ANOVA test (a statistical technique used to compare the sample means of two or more groups to determine if there is any significant difference among the population means) to compare the cut-in durations for all three groups. The samples are independently collected, and from Figure 78 we know that all sample groups are normally distributed, and the standard deviations for the groups are approximately equal, therefore the assumptions for one-way ANOVA test is met. The resulting test statistic is 0.263 and the p-value is 0.770, and at a significance level of 0.05 there is no sufficient evidence that any difference exists between all sample groups. Therefore, we conclude that the cut-in duration difference among the 3, 4 and 5 seconds headway is insignificant, possibly because the cut-in duration is mainly driven by the difference in speed between the intended speed of the vehicle and the speed of the trucks.

In the process of investigating the effects of cut-in maneuvers while platooning, an important aspect to consider is the speed of the trucks when the cut-in takes place, and more specifically, the difference in these speeds, i.e. difference between the speed of the leading truck and the speed of the follower truck. The lowest mean and maximum speed difference between the trucks were recorded when the headway was of 4 seconds, as seen in Figure 79. Usually when a cut-in takes place, the following truck's response is to reduce speed and disengage the platoon to accommodate for a new vehicle between the leading and following truck. The highest mean speed difference is 6.87 km/h for a headway of 5 seconds, and the maximum recorded speed difference was a difference of 16.35km/h for a headway of 5 seconds. The minimum recorded speed difference in contrast was recorded for a headway of 3 seconds at 1.44 km/h, which is a very minimal variation. From this point of view, a headway of 4 seconds seems to be more conducive to a safer driving experience as on average it required a smaller change of speed for the following truck. This is not only evidenced by the mean speed difference of 3.36km/h, but also the smallest standard deviation out of all headways, at 1.50 for a 4-second headway, compared to 3.16 for a 3-second headway and 4.66 for a 5-second headway. This speed difference could potentially imply a more efficient platooning, as it makes it easier to re-engage platooning once the cut-in vehicle proceeds to cut-off and change lanes.

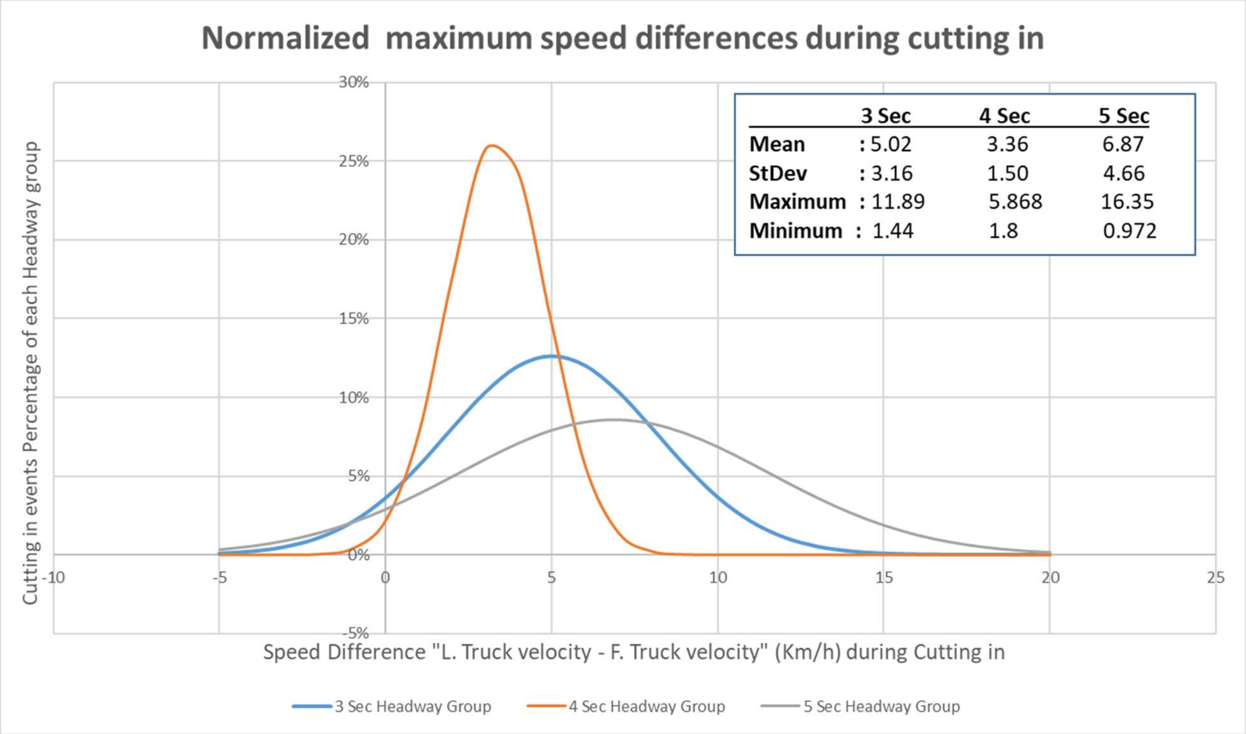


Figure 79. Normalized maximum speed differences during cutting in for different headways.

To better demonstrate the behavior of platoons during cut-in and cut-outs, Figure 80 shows how the speeds of the follower and lead trucks differ at the time the traffic vehicle cuts-in and before cut-out. In addition, there is a measure of 0 (disengaged) and 1 (engaged) to explain the status of the platoon. Figure 80 shows how the follower truck's speed dropped due to a cut-in, and the system disengaged instantly. The follower truck then started accelerating when there was enough space given to the traffic vehicle ahead. If there is not enough space, the acceleration of the follower truck will not begin until after the cut-out occurs. The system reengaged after the traffic vehicle cut-out and the required headway between the two trucks was met again.

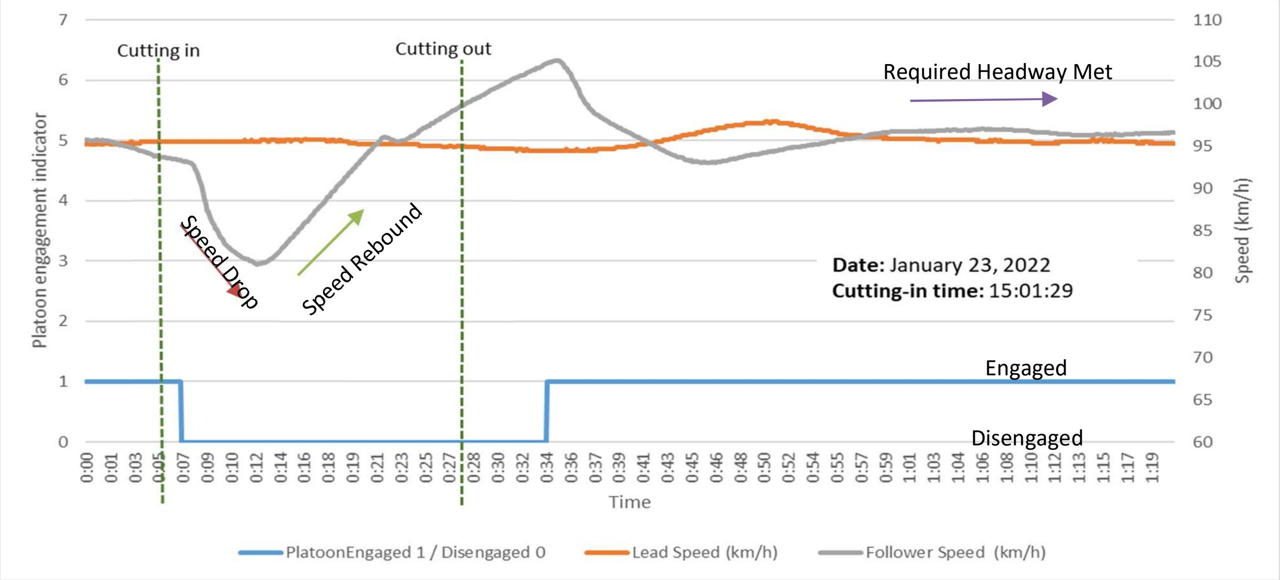


Figure 80. CTPS behavior during a traffic vehicle cut-in and out – Typical interaction

However, as shown in Figure 81, in some scenarios where the traffic vehicle cut-in is close to the lead truck, the system had the chance to reengage even before the cut-out occurred.

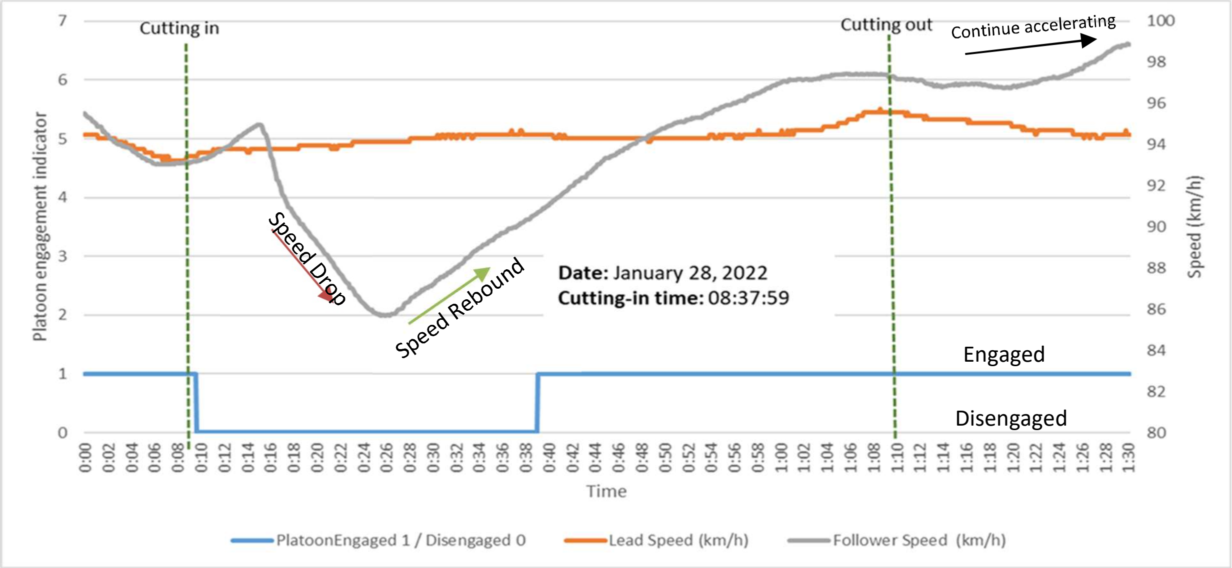


Figure 81. CTPS behavior during a traffic vehicle cut-in and out – System reengagement before cutting out

In 50 out of 52 cut-in occurrences, the system was instantly disengaged after the cut-in. However, as demonstrated in Figure 82, on two occasions the system took 3-5 seconds to disengage. In these cases, the traffic vehicle merged from an on-ramp very close to the lead truck, which allowed the platooning system to remain engaged for a couple of seconds before being interrupted. The position of the traffic vehicle – close to the lead truck – explains why the system reengaged for a few seconds before the follower truck got closer.

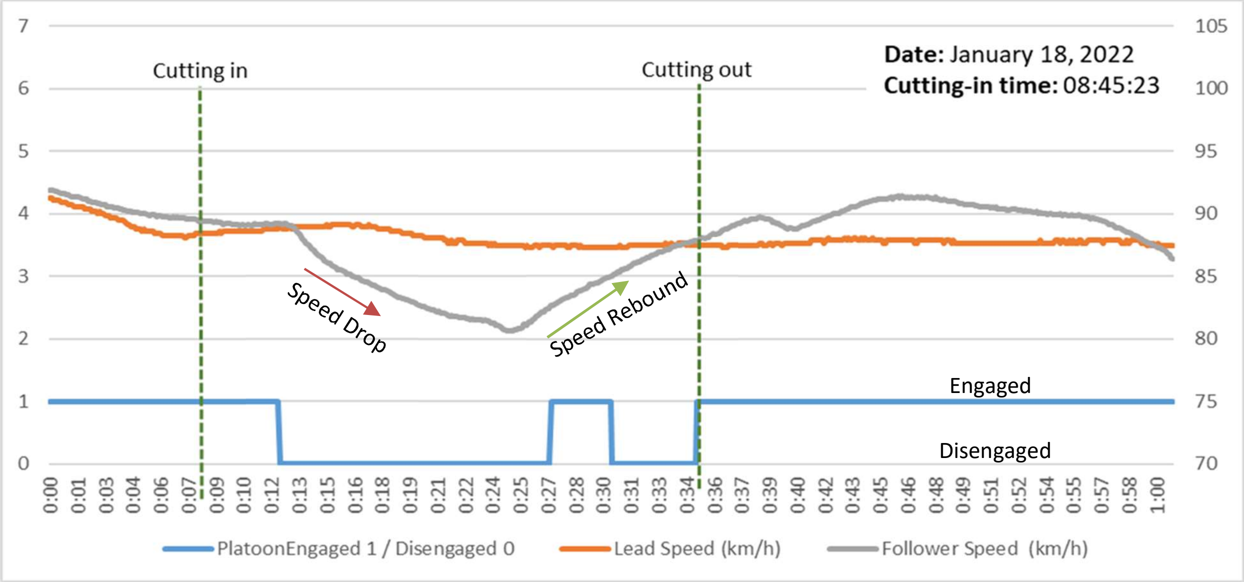
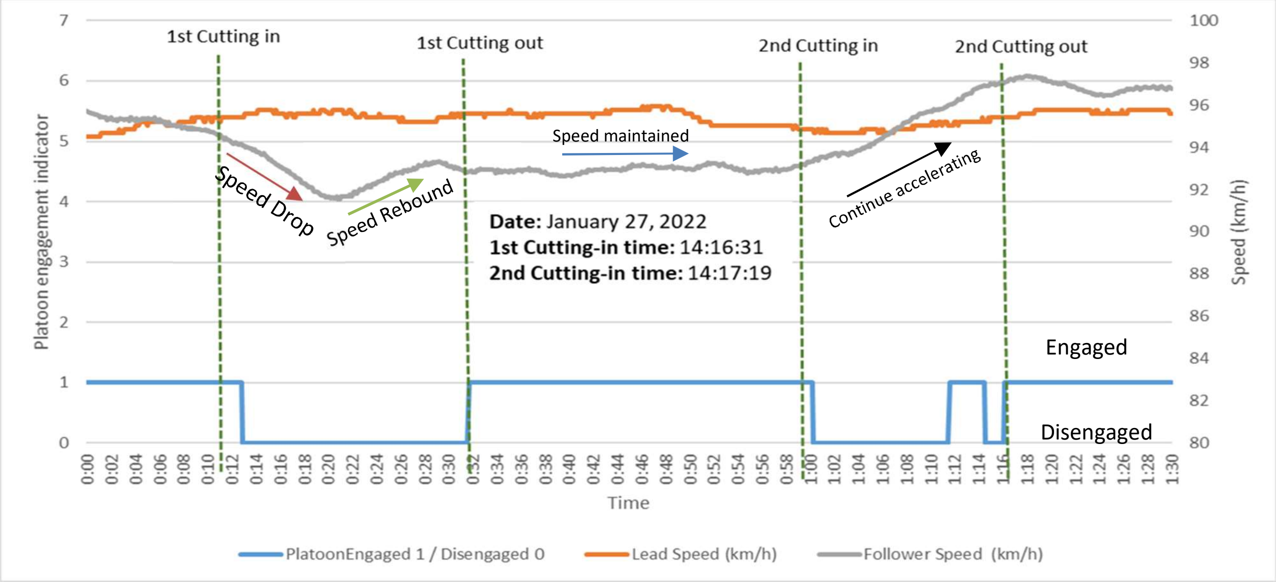


Figure 82. CTPS behavior during a traffic vehicle cut-in and out – Delayed Disengagement

In some high traffic volume situations, the potential for two cut-ins occurring is high, as observed in some cases during the trials. Figure 83 shows the platoon behavior during two cut-ins. At the first cut-in, the traffic vehicle was at 50 % quantile. Due to the cut-in, the follower truck decelerated and the platoon disengaged instantly. A few seconds after, the follower truck had enough space to accelerate again and the system successfully reengaged, although the required headway was not yet met. The follower truck's speed was maintained, as there was not enough space to accelerate more and meet the required headway. At the second cut-in, the traffic vehicle was at 75 % quantile and the platoon disengaged instantly. However, the follower truck's speed was not affected by the second cut-in as the traffic vehicle was close to the lead truck. A few seconds before the second cut-out, the follower truck accelerated again to meet the required headway between the trucks and the system reengaged successfully.



Date: January 27, 2022
1st Cutting-in time: 14:16:31
2nd Cutting-in time: 14:17:19

Figure 83. CTPS behavior during a traffic vehicle cut-in and out – Double cut-ins

8.2.2. Investigating the Platoon Interactions Responses

In the analysis of different scenarios of interaction with surrounding traffic, various response categorization were generated in regards to the platoon operations. Scenario 2 (follow random traffic vehicles) did not impact the platooning operations, and it was, understandably, the most common scenario. However, some other scenarios caused the interruption of platoon operations, at least briefly. Some scenarios are straightforward in the expected response to their occurrence, as is the case with scenario 4 (cut-outs), the system always tends to re-engage after a vehicle cuts-out and stops interrupting the platoon. Scenarios 6 and 7 usually imply a disengagement of the platoon. However, two scenarios (3 and 5) present mixed responses.

Scenario 3 (vehicle cut-ins) occurred 52 times during the trials, and all except two responses were instant disengagement of the platooning system. In the two scenarios this did not happen, the platoon kept engaged for about 3 seconds and then disengaged. These two responses were not drastically different to the usual response for this scenario, but they may have different implications as the system kept functioning for a brief moment. Out of these two instances, one did not present any different cut-in circumstances than usual. On the other occasion, the cut-in vehicle merged from an on-ramp very close to the lead truck, which permitted the platooning system to remain engaged for a couple of seconds before getting interrupted. Table 22 shows the matrix of each cut-in interaction conditions and platoon response.

The platooning system was operated in different weather conditions. However, the results did not show any substantial effect on whether the platoon would disengage in these conditions. The shortage of weather data for some scenario conditions in comparison to others did not support the ability to consider and investigate the relationship between the weather conditions, scenario conditions and platoon responses.

Table 22. Scenario #3 cut-in CTPS responses of (a) 3 sec, (b) 4 sec and (c) 5 sec Headway.

Interaction Condition	**Platoon Response**		**Grand Total**
	Instant Disengagement	**Delayed Disengagement**	
25% quantile	6.45%	0.00%	6.45%
Bare Dry	3.23%	0.00%	3.23%
Passing Clouds	3.23%	0.00%	3.23%
Bare Wet	3.23%	0.00%	3.23%
Mostly Cloudly	3.23%	0.00%	3.23%
50% quantile	70.97%	3.23%	74.19%
Bare Dry	54.84%	0.00%	54.84%
Clear	6.45%	0.00%	6.45%
Overcast	29.03%	0.00%	29.03%
Partly Sunny	9.68%	0.00%	9.68%
Passing Clouds	3.23%	0.00%	3.23%
Sunny	6.45%	0.00%	6.45%
Bare Wet	12.90%	3.23%	16.13%
Mostly Cloudly	6.45%	0.00%	6.45%
Partly Sunny	6.45%	3.23%	9.68%
Shoulder ice/snow	3.23%	0.00%	3.23%
Sunny	3.23%	0.00%	3.23%
75% quantile	16.13%	3.23%	19.35%
Bare Dry	16.13%	3.23%	19.35%
Clear	3.23%	0.00%	3.23%
Overcast	9.68%	0.00%	9.68%
Partly Sunny	3.23%	0.00%	3.23%
Passing Clouds	0.00%	3.23%	3.23%
Grand Total	93.55%	6.45%	100.00%

(a) 3 Sec Headway

Interaction Condition	Platoon Response Instant Disengagement
25% quantile	33.33%
Bare Dry	33.33%
Mostly Cloudly	16.67%
Sunny	16.67%
50% quantile	50.00%
Bare Dry	50.00%
Sunny	50.00%
75% quantile	16.67%
Bare Dry	16.67%
Sunny	16.67%
Grand Total	100.00%

(b) 4 Sec Headway

Interaction Condition	Platoon Response Instant Disengagement
25% quantile	33.33%
Bare Dry	33.33%
Mostly Cloudly	16.67%
Sunny	16.67%
50% quantile	50.00%
Bare Dry	50.00%
Sunny	50.00%
75% quantile	16.67%
Bare Dry	16.67%
Sunny	16.67%
Grand Total	100.00%

(C) 5 Sec Headway

Scenario 5 (vehicles crossing over) occurred 11 times during the trials, and the predominant response was to disengage briefly and then re-engage. The brief disengagement was due to the vehicle crossing over from one lane to the next, and driving in front of the following truck for a few seconds. However, two exceptions were found, in which there was no change and the platoon remained engaged. The reason the platoon remained engaged in these two occasions was that the crossover was fast and close to the leading truck, so the vehicle crossing over did not stay between the two trucks long enough to interrupt the platooning system. Table 23 shows the matrix of each cross-over interaction conditions and platoon response.

Table 23. Scenario #5 Traffic vehicle cross-over CTPS responses of (a) 3 sec and (b) 4 sec headway.

Interaction Condition	Platoon Response		Grand Total
	Disengaged only very briefly	Kept engaged	
50% quantile	16.67%	16.67%	33.33%
Bare Dry	0.00%	16.67%	16.67%
Overcast	0.00%	16.67%	16.67%
Bare Wet	16.67%	0.00%	16.67%
Mostly Cloudly	16.67%	0.00%	16.67%
75% quantile	50.00%	16.67%	66.67%
Bare Dry	50.00%	16.67%	66.67%
Clear	16.67%	0.00%	16.67%
Overcast	16.67%	0.00%	16.67%
Partly Sunny	16.67%	16.67%	33.33%
Grand Total	66.67%	33.33%	100.00%

(a) 3 Sec Headway

Interaction Condition	Platoon Response		Grand Total
	Disengaged	Disengaged only very briefly	
75% quantile	20.00%	80.00%	100.00%
Bare Dry	20.00%	80.00%	100.00%
Clear	0.00%	20.00%	20.00%
Mostly Cloudly	0.00%	20.00%	20.00%
Passing Clouds	0.00%	20.00%	20.00%
Sunny	20.00%	20.00%	40.00%
Grand Total	20.00%	80.00%	100.00%

(b) 4 Sec Headway

8.2.3. Investigating the Operational Impacts of Using a CTPS and the Operational Design Domain (ODD)

From an operational point of view, several impacts could be assessed, described below.

1) Increased road use efficiency. Multiple studies have shown that frequent lane-changing maneuvers have a negative impact on driving speed, travel time and headway as the traffic density increases [1, 2, 3]. During the trials, only one time did the trucks perform a lane change (characterized by scenario 7), this means that the trucks were not very intrusive

for surrounding traffic in this aspect, and could remain in their respective lanes, maintaining their desired speed for longer periods of time, without having a significant effect on the surrounding traffic.

2) Improved safety via advanced collision avoidance. We can attest from the video data retrieved during the trials that there were zero cases of near-miss scenarios. Not once was a potentially dangerous unplanned event detected while the platoon was engaged. This was corroborated with the worst-case follower truck deceleration event of $-2m/s^2$ for a particular cut-in event. A hard braking event takes place when a vehicle decelerates by less than -0.45g or $-4.41m/s^2$ [4][5]. Scenarios of hard braking are fairly common on highways, especially when construction zones or crashes take place on the roads. However, these scenarios did not occur during the platooning trials.
3) Scheduling. The trucks arrived at their destination on time for most of the trials, permitting the conclusion that the platooning was not detrimental to the fulfillment of deliveries due to time constraints. Most disruptions were attributed to pre/post-test activities requiring incremental time.
4) Cargo configuration and weight. Weight and cargo composition did not seem to impact the behavior of the platoon or the operations significantly. The project instituted an operational requirement for the lead truck to be heavier than the follower truck. This did necessitate changing trailers on occasion and advising Bison dispatch of the change. There was also a trip whereby the follower truck was heavier and the driver was reluctant to engage platooning.
5) Speed. Trucks were able to maintain a similar speed for most of the time, as long as platooning was not interrupted by external factors such as cut-ins by random traffic vehicles. This suggests a higher control and efficiency during the process of transportation of goods.

The Operational Design Domain ODD for this specific CTPS is unique to this project but the operational considerations investigated could be applied to similar automated driving systems in other geographies. Some emerging technologies (i.e., DSRC, CV2X) have been used on other demonstrated platoon systems. Those other technologies have been designed for V2V applications to achieve more reliable low latency communication, which can allow reduced headway between trucks in a platoon, while this CTPS only depend on an LTE network for V2V communication. In addition, in order to investigate the ODD, some key factors could be assessed, described below.

1) Road Geography and Geometry: The road terrain e.g. road grade, curvature did not have much effect in the ADS ability to maintain vehicle speed and position in the center of the lane.

2) Roadway Type: The operation of platoons is only recommended on multilane, divided, controlled-access highways. Highway 2 has 3 lanes for most the distance between Edmonton and Calgary, however 2 lanes segments also exist.

3) Weather Conditions: In this project, truck-platooning system was operated in different weather conditions such as overcast, sunny, snowy and cloudy. However, they was no relationship found between the different types of weather and the platoon performance. Due to snow covered road conditions there were several days whereby the

driver decided to not engage the system.

4) Time of a Day: Both day and night trips were included in this platoons trials. However, the performance of the front camera used in investigating these trials was lower at night. Therefore, primary attention was given to those recorded day trips.

9. Summary and Conclusions

This project included extensive vehicle instrumentation to collect data from two class 8 trucks under various driving conditions under platooning and non-platooning operations. We conducted over 26,000 km of truck testing in Oct 2021 and Jan 2022. Over 1 TB of collected data including platoon operation, powertrain, vehicle, traffic interaction, and weather data. This included platooning data for traveling distance of 3,150 km, and the total platooning duration of 2,075 minutes. The main findings from this study include:

1. The results confirm the feasibility and demonstration of truck platooning in commercial setting under Canadian winter climate conditions. These include platooning under ambient temperature as cold as -27 °C with road surface conditions ranging from dry to partly covered snow and shoulder ice/snow.
2. The platooning engagement ratio could reach up to 96% on the selected Hwy-2 route, while the average engagement ratio among 28 platooning trips was more than 55%.
3. There was about 1 sec difference between commanded and achieved platooning distance during the trials. To this end, the average effective platooning distances between lead and follower trucks were approximately 4, 5 & 6 sec during the trials. This was due to the safety buffer in the platooning controller design, uncertainty/error in calculating the platoon distance during real-time operation because of data latency during signal transmission and error from sensor fusion in the utilized CTPS system.
4. No benefit for fuel saving was observed in the studied platooning system. In fact, the fuel consumption of the follower truck was generally more than the lead truck during platooning when considering the difference between fuel consumption of lead and follower trucks under baseline (non-platooning) conditions. This was because of no significant aerodynamic drag reduction expectations with large platoon distances (> 100 m) studied in this project. Furthermore, the follower truck had a less smooth speed and power profile compared to the lead truck.
5. The effects of platooning on fuel saving was difficult to assess when the weights of lead and follower trucks are different. This is due to variations in engine operating conditions caused by substantially different traction power needs. In other words, weight is a much stronger factor compared to the platooning effect to influence on specific truck fuel consumption (kg/ton.100 km) of commercial trucks.
6. Extensive data confirmed much higher fuel consumption (kg fuel/ton.100 km) at light-load conditions vs full-load conditions. This is due to the engine operating at low thermal efficiency (i.e., low fuel conversion efficiency) regions when a truck is lightly loaded.
7. The follower truck braked more frequently than the lead truck during platooning. This increases fuel consumption in the follower truck.

8. There were more braking events by the follower truck at 5 sec versus 3 sec platoon distance. This can be explained by more cut-ins by traffic vehicles at 5 sec vs 3 sec platooning distance.
9. The follower truck generally had more vehicle speed fluctuations. This increases fuel consumption in the follower truck. This also caused more transient engine-out NOx emissions by the follower truck compared to the lead truck.
10. Significant power fluctuations were observed in the follower truck compared to the lead truck during platooning. Frequent platooning engagement and re-engagement contributed to the power fluctuations in the follower truck. This can have adverse effect on the engine life.
11. Smooth platooning operation was observed under flat road (minimal road gradient change) driving conditions and when no sudden braking/acceleration was needed due to traffic conditions. The fuel consumption by the follower truck also did not increase under these conditions. This may promote the benefits of platooning on flat roads with light traffic if a larger separation distance must be adhered to. In this project, the 3-sec platoon distance was the minimum value permitted by Alberta Transport.
12. Trips with empty trailer (light truck arrangement) showed higher specific NOx emissions (g/ton.100km). Specific NOx varied from 10 to 34 g/ton of truck over 100 km. For the truck heavy configurations, specific NOx values were close to 10 g/(ton.100km).
13. AIC fuel flow meter measurements and ECU reported values for fuel consumption had 0.3% to 14% difference depending on engine operating conditions. The AIC fuel flow meter was found useful for cumulative segment-wise (e.g., 2-min) event analysis, while ECU fuel consumption estimations are useful for instantaneous (sec-by-sec) analysis of the engine and powertrain performance during platooning.
14. The results showed that there is a higher frequency rate of cut-in when there was a larger platooning separation distance or when the headway was 5 seconds in comparison to the case when the headway was 4 seconds or 3 seconds.
15. The platooning system attempted to re-engage immediately following a traffic vehicle cut-out. Although, when the headway was 5 seconds, the platoon system generally re-engaged prior to the cut-out completion.
16. In regard to the preferred headway, a headway of 4 seconds presented improved responses in terms of speed reduction during traffic vehicles cut-in scenarios.
17. The platooning system tended to present less disruptions when the traffic vehicles cut-in or crossing over did it in a faster manner and closer to the leading truck. This allowed the follower truck to more smoothly adjust to the change in traffic conditions.

Overall, an optimum time-varying platoon distance could be selected considering safety while providing fuel savings. Larger platoon separation distances led to more cut-ins by neighboring vehicles, more engine power fluctuations, more engine-out NOx emissions and less opportunity for fuel savings.

We expect the platooning performance could be improved further when the cooperative truck platooning systems includes further coordination and control integration between platooning control systems and vehicle powertrain ECUs. This would mitigate speed and power variations resulting in improved safety and potential fuel savings.

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Appendix A: On-Road tests

A total of 41 trips were conducted on Highway 2 between Calgary and Edmonton between January 12, 2022 and January 30, 2022. Here are details of each trip:

No.	Test Date	Test Trip*	Test Type	Platooning Distance (s)	Time	Note
1	Jan 12	E-C	CTPS	3	Day	Shakedown test
2	Jan 13	C-E	CTPS	5	Day	
3	Jan 13	E-C	CTPS	3	Day	
4	Jan 13	C-E	Baseline	N/A	Night	
5	Jan 13	E-C	Baseline	N/A	Night	
6	Jan 14	C-E	CTPS	5	Day	
7	Jan 14	E-C	CTPS	3	Day	
8	Jan 14	C-E	Baseline	N/A	Night	
9	Jan 14	E-C	Baseline	N/A	Night	
10	Jan 15	C-E	CTPS	3	Day	
11	Jan 15	E-C	CTPS	3	Day	
12	Jan 16	C-E	CTPS	3	Day	
13	Jan 16	E-C	CTPS	3	Day	
14	Jan 17	C-E	Baseline	N/A	Day	
15	Jan 17	E-C	Baseline	N/A	Day	
16	Jan 18	C-E	CTPS	5	Day	
17	Jan 18	E-C	CTPS	3	Day	
18	Jan 19	C-E	Baseline	N/A	Day	AB2 was out of service
19	Jan 19	E-C	Baseline	N/A	Day	AB2 was out of service
20	Jan 20	C-E	CTPS	3	Day	
21	Jan 20	E-C	CTPS	3	Day	
22	Jan 21	C-E	ADAS	N/A	Day	AB1 was out of service
23	Jan 21	E-C	ADAS	N/A	Day	AB1 was out of service
24	Jan 22	C-E	CTPS	3	Day	
25	Jan 22	E-C	CTPS	4	Day	
26	Jan 23	C-E	CTPS	3	Day	
27	Jan 23	E-C	CTPS	5	Day	
28	Jan24	C-E	CTPS	5	Day	
29	Jan 24	E-C	CTPS	3	Day	
30	Jan 25	C-E	CTPS	5	Day	
31	Jan 25	E-C	CTPS	3	Day	
32	Jan 26	C-E	CTPS	3	Day	

33	Jan 26	E-C	CTPS	4	Day	
34	Jan 27	C-E	CTPS	3	Day	
35	Jan 27	E-C	CTPS	3	Day	
36	Jan 28	C-E	CTPS	3	Day	
37	Jan 28	E-C	CTPS	5	Day	
38	Jan 29	C-R	ADAS	N/A	Day	Traffic caused by protest
39	Jan 29	R-C	ADAS	N/A	Day	Traffic caused by protest
40	Jan 30	C-E	CTPS	4	Day	
41	Jan 30	E-C	CTPS	4	Day	

*C stands for Calgary, E stands for Edmonton, and R stands for Red Deer.

Appendix B: Definitions of Different Road Surface Conditions

All the definitions and pictures in this appendix are from https://511.alberta.ca/about/tutorial.

The 80/20 Rule

The 80/20 rule suggests that if more than 20% of the least preferred condition exists then the least preferred condition is the condition reported for that road segment.

Road is Bare

Figure B1 shows the road condition is bare.

Bare and dry: Within the segment, most of the road surface is bare and is free from wet areas and frozen precipitation.

Bare and wet: Within the segment, most of the road surface is moist or wet.

Figure B1: Bare road

Road is Partly Covered

Figure B2 shows the road condition is partly covered.

Partly Ice Covered: Within the segment, two wheels are on bare surface and other wheels likely on ice.

Partly Snow Covered: Within the segment, two wheels are on bare surface and other wheels likely on loose snow.

Partly Snow Packed: Within the segment, two wheels are on bare surface, other wheels likely on snow bonded with road.

Figure B2: Partly covered road

Road is Covered

Figure B3 shows the road condition is covered.

Ice Covered: Within the segment, all wheels are on ice.

Snow Covered: Within the segment, all wheels are on loose snow.

Snow Packed: Within the segment, all wheels are on snow bonded to road.

Figure B3: Covered road

Snowing

Figure B4 shows the road condition is snowing. Within the segment, snowflakes are falling from the sky.

Figure B4: Snowing road

Strong Wind

Figure B5 shows the road condition is strong wind. When there is a wind warning for your area, you should expect inland winds to be blowing steadily at 60-65 km/h or more, or winds that are gusting up to 90 km/h or more.

Figure B5: Strong wind road

Freezing Rain

Figure B6 shows the road condition is freezing rain. When rain or drizzle falls onto sub-zero surfaces and freezes on contact forming a layer of ice.

Figure B6: Freezing rain road

Fog

Figure B7 shows the road condition is foggy. Within the segment fog is present and as a result visibility is less than 500 meters. Driving any vehicle in low visibilities due to fog can be hazardous; therefore speeds should be reduced accordingly.

Figure B7: Foggy road

Drifting Snow

Figure B8 shows the road condition is drifting snow. Within the segment previously fallen snow is being transported through the air or across the pavement by wind, causing snow to mound up.

Figure B8: Drifting snow road

Shoulder Ice/Snow

Figure B9 shows the road condition is shoulder ice/snow. Within the segment, the shoulder (the portion of a highway that provides lateral support to the roadway) is covered or packed with snow or ice.

Figure B9: Shoulder ice/snow road

Appendix C: Collected Sensor Data Parameters

Data Resource	Parameter	Unit
SAE J1939	Trans Output Shaft Speed	rpm
	Engine Percent Load At Current Speed	%
	Estimated Pumping Percent Torque	%
	Engine Percent Torque Driver Demand	-
	Engine Percent Torque Actual	%
	Engine Speed	rpm
	Transmission Actual Gear Ratio	-
	Transmission Current Gear	-
	Yaw Rate	rad/s
	Lateral Acceleration	m/s^2
	Longitudinal Acceleration	m/s^2
	EGR1_Mass Flow Rate	kg/h
	Engine Intake Air Mass Flow Rate	kg/h
	Aftertreatment1_Intake NOx	ppm
	Aftertreatment1_Intake O2	%
	Aftertreatment1_Outlet NOx	ppm
	Aftertreatment1_Outlet O2	%
	Pitch Angle Extended Range	deg
	Aftertreatment1 Particulate Sensor	mg/m^3
	Aftertreatment2 Particulate Sensor	mg/m^3
	EGR2_Valve2_Position	%
	Commanded Engine Fuel Rail Press	MPa
	Commanded Engine Fuel Injection Ctrl Press	MPa
	High Res Engine Trip Fuel	L
	Aftertreatment1_DOC Intake Gas Temp	deg C
	Aftertreatment1_DOC Outlet Gas Temp	deg C
	Aftertreatment1_DOC Differential Press	kPa
	Aftertreatment1_SCR Catalyst Outlet Gas Temp	deg C
	DPF1_Soot Load Percent	%

DPF1_Time Since Last Active Regen	s
Aftertreatment1_DPF Soot Load Regen Threshold	%
DPF Inlet Press1	kPa
DPF Outlet Press1	kPa
EGR1_Valve Position	%
Commanded Engine Intake Manifold Press	kPa
Aftertreatment1_DEF Concentration	%
TurboVariable Geometry Actuator1	%
Aftertreatment1_DPF Differential Press	kPa
Aftertreatment1_DPF Outlet Gas Temp	deg C
Aftertreatment1_EGT	deg C
Aftertreatment1_DPF Intake Gas Temp	deg C
Aftertreatment1_DEF Tank Level1	%
Lane Tracking Status Right Side	-
Lane Tracking Status Left Side	-
Lane Departure Indication Enable Status	-
Front Axle Left Wheel Speed	km/h
Front Axle Right Wheel Speed	km/h
Rear Axle Left Wheel Speed	km/h
Rear Axle Right Wheel Speed	km/h
Speed Of Forward Vehicle	km/h
Distance To Forward Vehicle	m
Adaptive Cruise Control Set Speed	km/h
Road Curvature	km
Powered Vehicle Weight	kg
Gross Combination Vehicle Weight	kg
Battery Potential Power Input2	V
Engine Pre Filter Oil Press	kPa
Engine Exhaust Gas Press1	kPa
Instantaneous Est Brake Pwr	kW
Turbo1 Compressor Inlet Temp	deg C
Engine ECU Temp	deg C

	EGR1_Temp	deg C
	Service Brake Circuit1 Air Press	kPa
	Service Brake Circuit2 Air Press	kPa
	Front Axle Speed	km/h
	Relative Speed Front Axle_Left Wheel	km/h
	Relative Speed Rear Axle1_Right Wheel	km/h
	Relative Speed Rear Axle2_Left Wheel	km/h
	High Resolution Total Vehicle Distance	km
	Engine Injector Metering Rail1_Press	MPa
	Engine Total Idle Hours	hr
	Engine Turbo charger1 Speed	rpm
	Estimated Engine Parasitic Loss_Percent Torque	%
	Engine Total Operation Hours	hr
	Engine Total Fuel Used	L
	Engine Coolant Temp	deg C
	Engine Oil Temp1	deg C
	Engine Oil Pressure	kPa
	Engine Crankcase Pressure	kPa
	Wheel Based Vehicle Speed	km/h
	Engine Fuel Rate	L/h
	Engine Instantaneous Fuel Economy	km/L
	Barometric Press	kPa
	Ambient Air Temp	deg C
	Engine Intake Manifold1_Press	kPa
	Engine Intake Manifold1_Temp	deg C
	Battery Voltage PowerInput1	V
	Platoon Engaged	-
	Copilot Engaged	-
CTPS-CAN	Pronto Error	-
	Cruise Ctrl Switch	-
	Steer Mismatch	-
	Poor Lane Markings	-

Time Gap	s
Set Speed	mph
Lead Driver Brake	-
Lead Driver Throttle	-
Lead Engaged	-
Link Latency	s
Lead Lat Dist	m
Lead Lon Dist	m
Lead Throttle	-
Lead Brake	psi
Lead Accel	m/s^2
Lead Speed	m/s
Driver Brake	-
Driver Throttle	-
Throttle	-
Applied Brake Pressure	psi
Supply Brake Pressure	psi
Steer Angle	deg
Steer Rate	deg/s
Latitude	-
Longitude	-
Yaw	deg
Pitch	deg
Roll	deg
Altitude	m
Speed	m/s
Accel Lon	m/s^2
Accel Lat	m/s^2
Radar Lead Lat Dist	m
Radar Lead Lon Dist	m
Radar Lead Rel Speed	m/s
Radar Lead Idx	-

	Idx	-
	Dist Lon	m
	Dist Lat	m
	V Rel Lon	m/s
	Dyn Prop	-
	V Rel Lat	m/s
	Rcs	dBm^2
DEWE 43A	Total Consumption	L
	Fuel Consumption By Derivative	L/h
	Fuel Consumption from Frequency	L/h
	Fuel Consumption from Frequency/Filter	L/h
	Frequency	Hz
	Raw_Count	-
	Raw_Count/MIN	Hz
	Raw_Count/MAX	Hz
	1Hz Consumption	L/h
	Calculated Seperation Gap	s
	Lead Speed	km/h
	Follower Speed	km/h
	Wheel Based Vehicle Speed	km/h
	Percent Load	%
	Engine Speed	rpm
	Cabin Camera	Frames
	Road Camera	Frames
	Our Calculated Engine Torque	Nm

Appendix D: Installation of the Fuel Flow Meter

In order to review measured fuel consumption from AIC flow meters, two tests were planned for AB1 and AB2 trucks on 1st and 2nd of November 2021. The result of measured fuel consumption from the AIC flow meter was compared with two other references of fuel consumption. The first reference was calculated value of fuel consumption from engine ECU collected from SAEJ1939. The second reference was the truck industry norm of fuel consumption named as calculated value. Figure D1 shows fuel consumption at constant speed of 100 km/h for a part of the road section. In this road section there was little variation in the engine torque and power due to changing road grade and wind speed. As expected, based on the preliminary fuel consumption results, the AIC flow didn't show an identical value compared to other references of fuel consumptions (engine reported value and trucking industry norm calculated value). The measured fuel consumption from the AIC flow meter was almost two times the amount of two other references. This evidence indicated a problem.

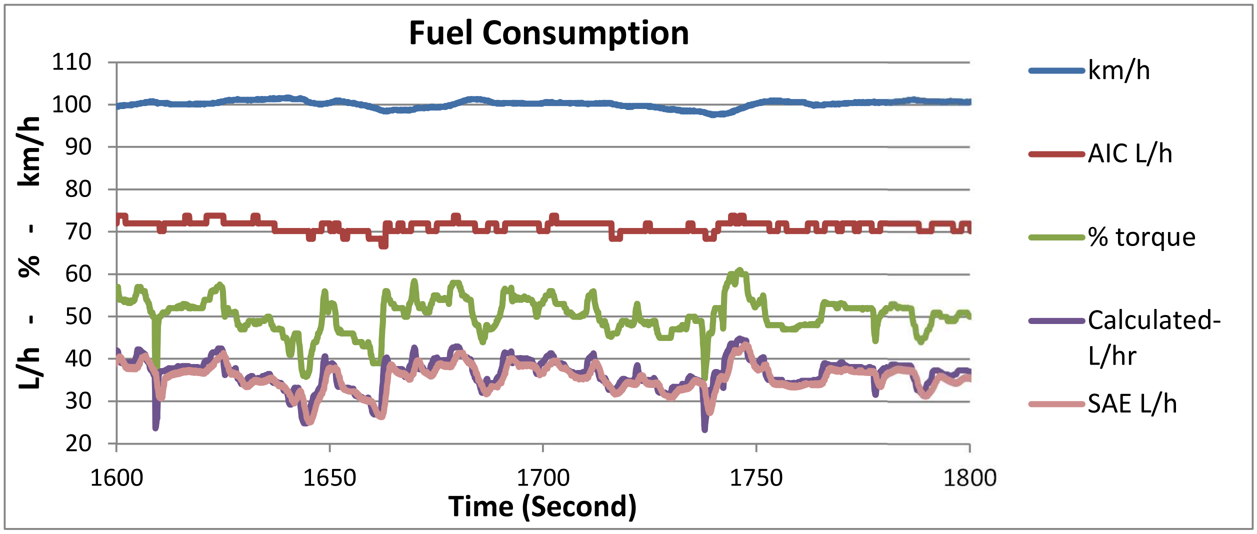


Figure D1: Fuel consumption in part of road where speed was 100km/h constant (Cruise control)

For all the trips we had on Nov. 1 and Nov. 2 (from Calgary to Edmonton, Edmonton to Red Deer and return and for trip from Edmonton to Calgary) we had similar results to the Figure D1.

After analyzing the results of all the trips, we concluded that the issue with the AIC flow meters was serious and was decided to have the trucks in Bison transport workshop for closer inspection and potential repair.

After inspection and checking all the connections and settings it was observed that there was a special facility in the fuel intake line. Because of having a TRV (Thermal Recirculation Valve) on the engine the intake fuel line to the engine was connected to a return fuel pipe flow. The function of the TRV valve was to change the amount of returned flow based on the fuel temperature. As the initial installation was located inside that loop, the measured flow accounted for the internal circuit flow rather than the flow to the engine. So, the suggested solution was to change the piping and locate the AIC flow meter at the upstream location of the flow where the TRV valve is not affecting.

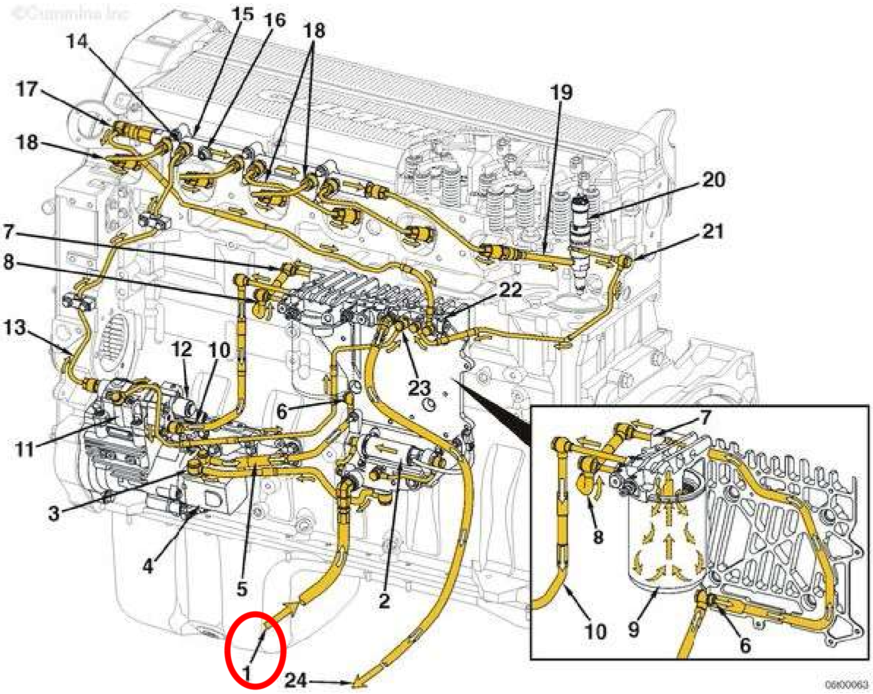


Figure D2: Fuel piping of Cummins ISX 15 without TRV (From Cummins website)

In Figure D2, the fuel feeding line to the engine without TRV is shown. In these kinds of engines, the engine intake hose is taking the fuel from water separator. At the initial setting, the pipe outlet from water separator is taken to the fuel flow meter and the connection from fuel flow meter connected to the position 1. As the piping described for this type of engine was not compatible for existing Peterbilt trucks, the piping changed based in the specification of the engine with TRV valve.

Figure D3: Fuel connections at driver side of engine, the connections were inspected as much as possible at AMTA yard

In Figure D3, the piping for the AIC flow meter before considering the TRV valve is shown. As a function of TRV some warm fuel returns back to heat the intake fuel from the tank. The proportion of the warmed fuel to the cold fuel is not known at any working point. So, the higher flow residing at first installation is because the actual return flow was not returning back to the flow meter.

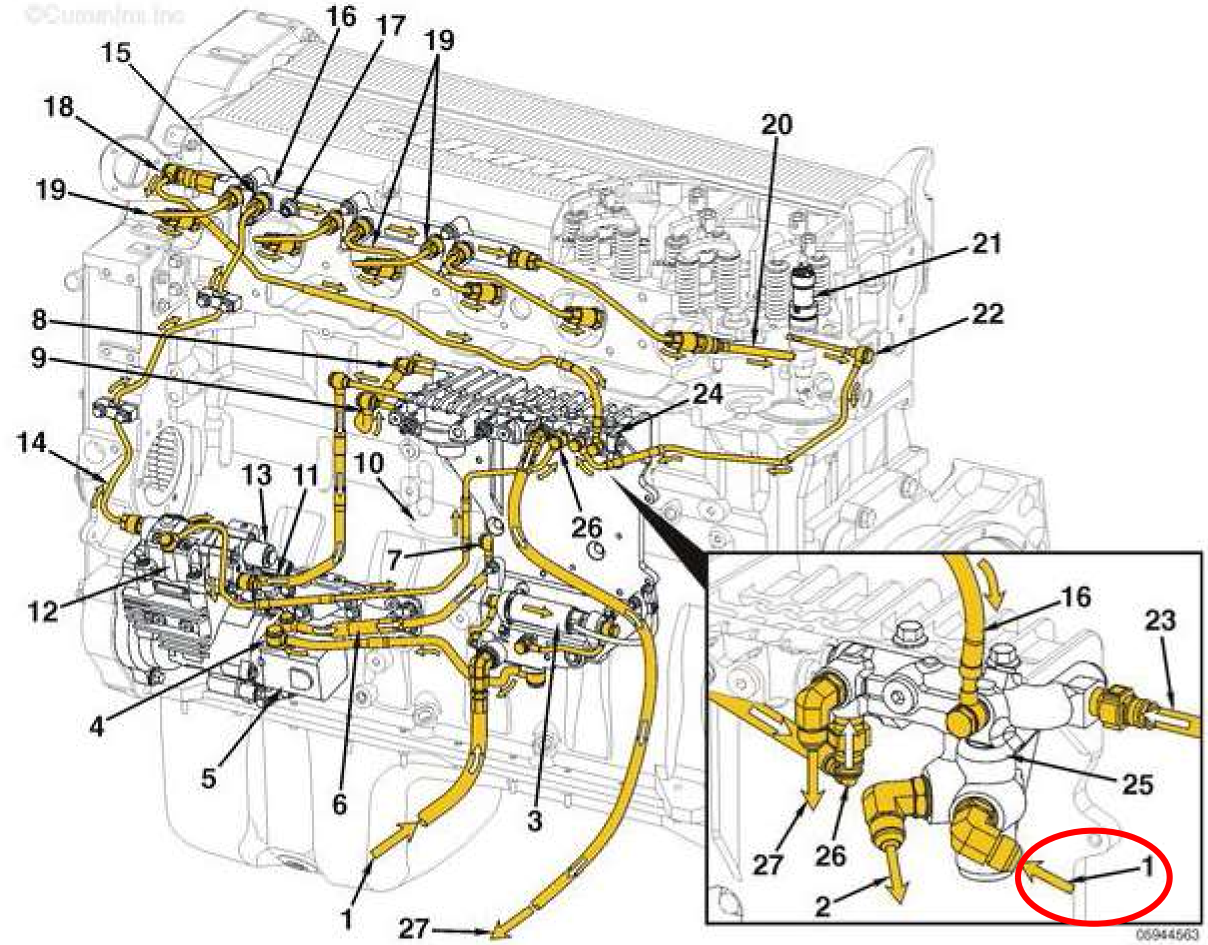


Figure D4: Fuel piping of Cummins ISX 15 with TRV- AB1 and AB2 engine type (From Cummins website)

In Figure D4, the shown connection No. 1 is taking the fuel from tank to the water separator. At the final installation, the shown connection is piped to the fuel flow meter and the intake hose to the water separator, connected to the fuel flow meter. In this way all the return circuits are remaining inside the consumption circuit to the fuel tank therefore they are considered in the reading from AIC flow meter.

After installing the system for both the AB1 and AB2 trucks, the air bleeding process continued to make trucks ready for road test.

After making the trucks ready for the road, a road test carried out. The result of test and measured fuel consumption for a section of road at the constant speed of 100km/h reviewed. Result of fuel consumption beside engine torque and power and truck speed was demonstrated for 4 minutes and 10 second of the test trip in Figure D5.

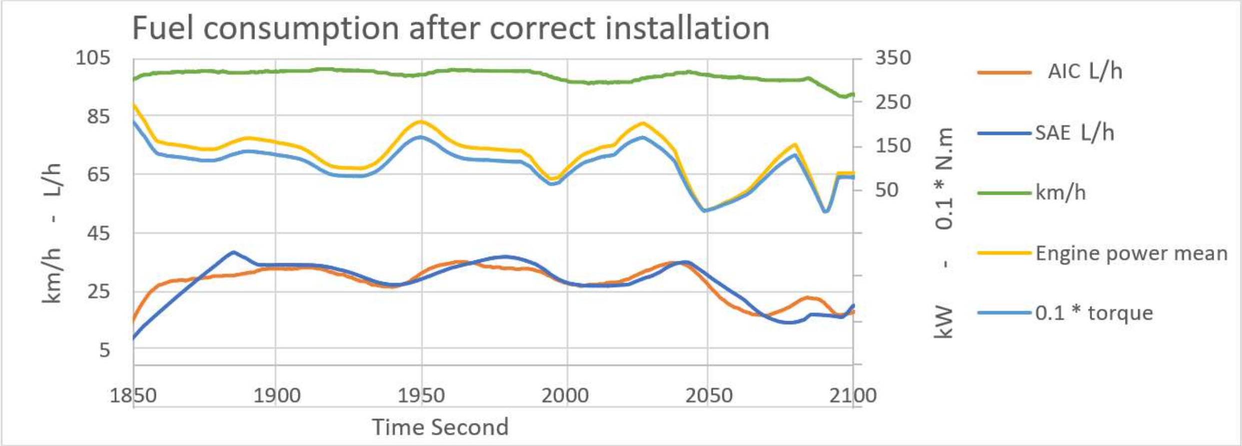


Figure D5: Fuel consumption graph from AIC and engine ECU show similar results at speed of 100 km/h

A true instantaneous reading of idling fuel consumption is shown in Figure D6. The value of 3.22 L/h fuel consumption is only for a moment. According to observation done the fuel rate value varies from 2.6 to 3.6 L/h.

Figure D6: True reading at idle working condition

Figure D7: Air bleeding of AIC fuel flow meter

After changing the piping installation, the AIC flow meter placed on the floor to use the gravity and bleed the air from the pipes completely, as shown in Figure D7.

Final piping installation and its configuration is shown in Figure D8.

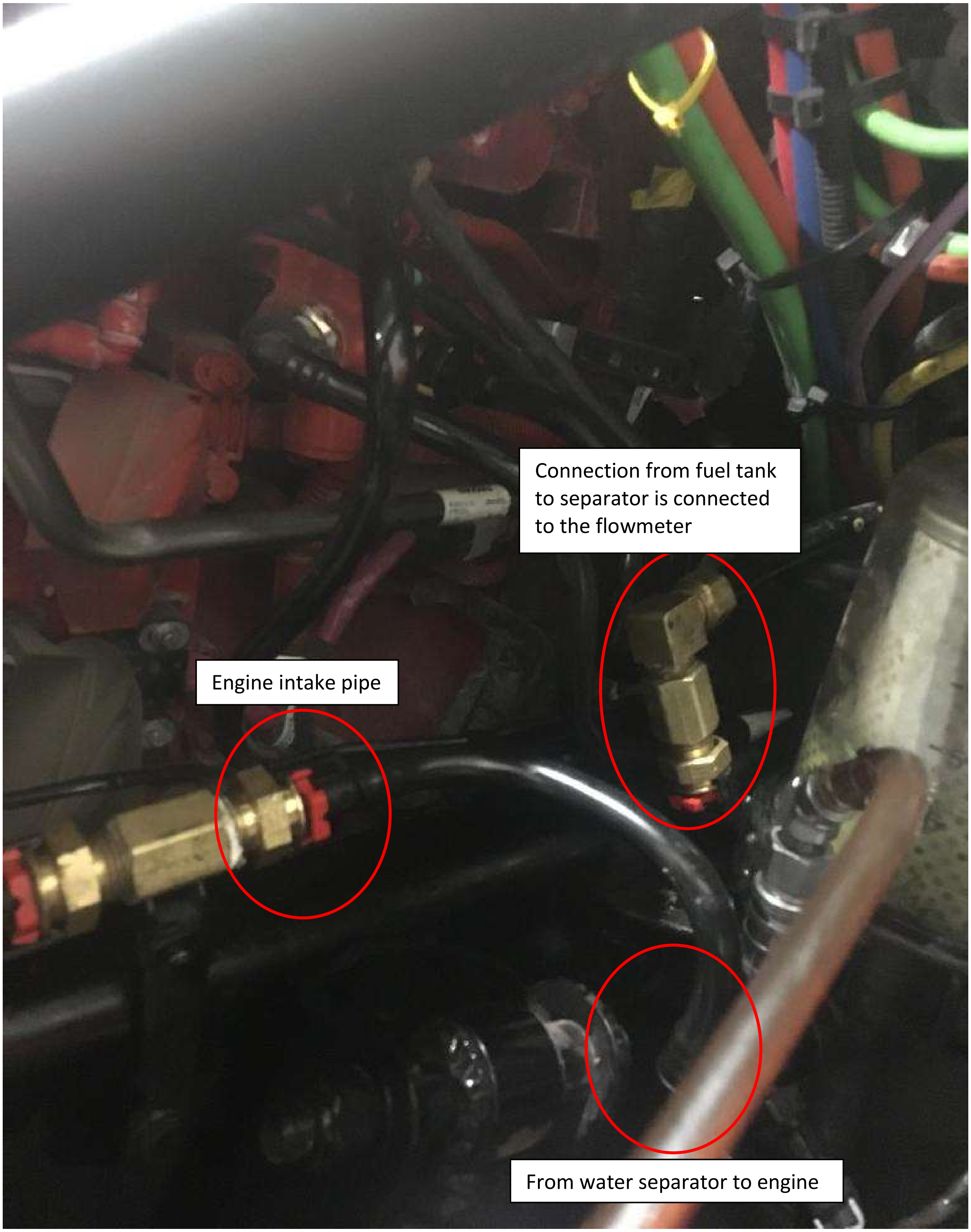


Figure D8: Fuel line connection changes

Appendix E: Wind Measurements Calibration

Before the trials, the research team performed the wind measurements calibration to adjust the on-truck mobile weather station wind speed and angle measurements by using the data from the selected on-road stationary weather stations (circled in blue), as shown in Figure E1. There is a total of 117 stations in the network called Environment Sensing Stations, which are the large part of Road Weather Information System (RWIS). These weather stations are owned by Alberta Transportation. Some of these weather stations are positioned at 50 km spacing while some are placed at a distance of 5-20 km. The data recording frequency of the on-road stationary weather stations is significant for the calibration process, and the lowest time frame is 5 minutes. The shorter the time frame the more accurate the analysis.

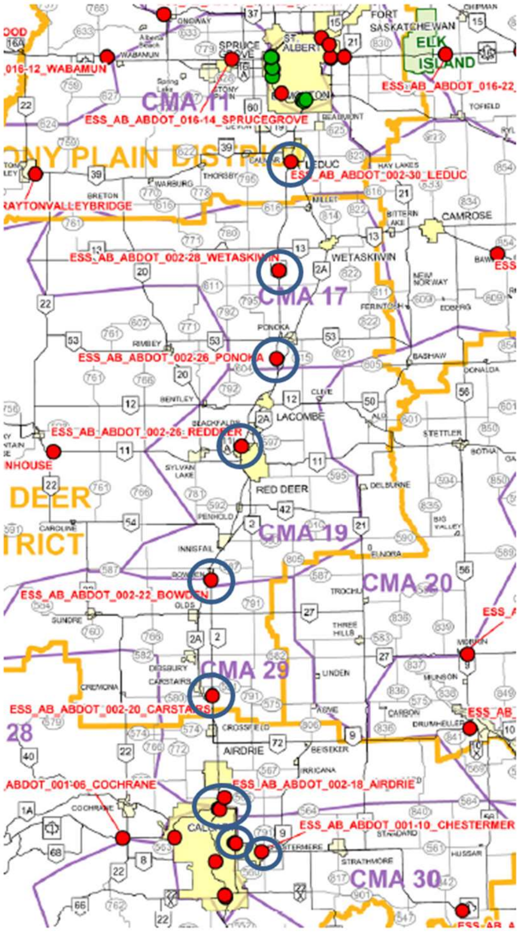


Figure E1: On-road stationary weather stations

A total of 10 weather station were used in weather calibration analysis. Locations of these weather stations are given in Table E1.

Table E1: Locations of the on-road stationary weather stations

No.	Location	Longitude	Latitude
1	ESS_AB_ABDOT_001-10 CHESTERMERE	51.038060	-113.786960
2	ESS_AB_ABDOT_201-08 STONEY N HWY 2 NW	51.177100	-114.002660

3	ESS_AB_ABDOT_002-18 AIRDRIE	51.212700	-113.971350
4	ESS_AB_ABDOT_201-02 TCHE NW	51.067990	-113.924190
5	ESS_AB_ABDOT_002-20 CARSTAIRS	51.533700	-114.026720
6	ESS_AB_ABDOT_002-22 BOWDEN	51.903060	-114.025940
7	ESS_AB_ABDOT_002-26 RED DEER	52.331100	-113.856950
8	ESS_AB_ABDOT_002-26 PONOKA	52.608320	-113.665010
9	ESS_AB_ABDOT_002-28 WETASKIWIN	52.889640	-113.644390
10	ESS_AB_ABDOT_002-30 LEDUC	53.235940	-113.569270

The following formulas were then used to calculate the true wind velocity and angle relative to the truck:

$$V_{true} = \sqrt{V_w^2 + V_T^2 + 2V_wV_T\cos(\phi)} \tag{3}$$

$$\psi_{true} = \tan^{-1}\left(\frac{V_w \sin\phi}{V_T + V_w\cos\phi}\right) \tag{4}$$

where V_{true} is true wind velocity, ψ_{true} is true wind angle, V_w is wind velocity measured by the on-road weather station and V_T is lead truck speed. The above equations are found by solving the following velocity vector diagram, as shown in Figure E2.

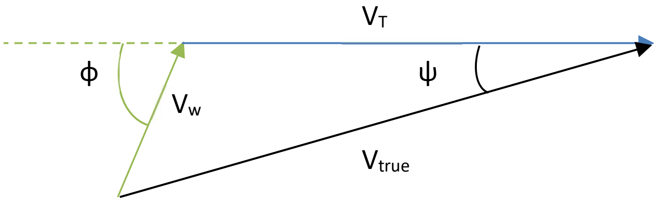
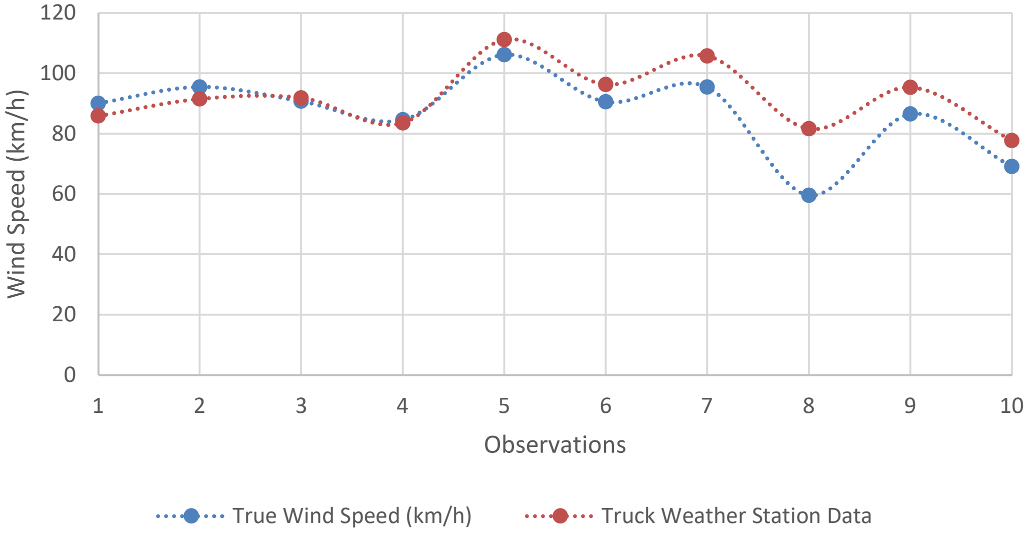
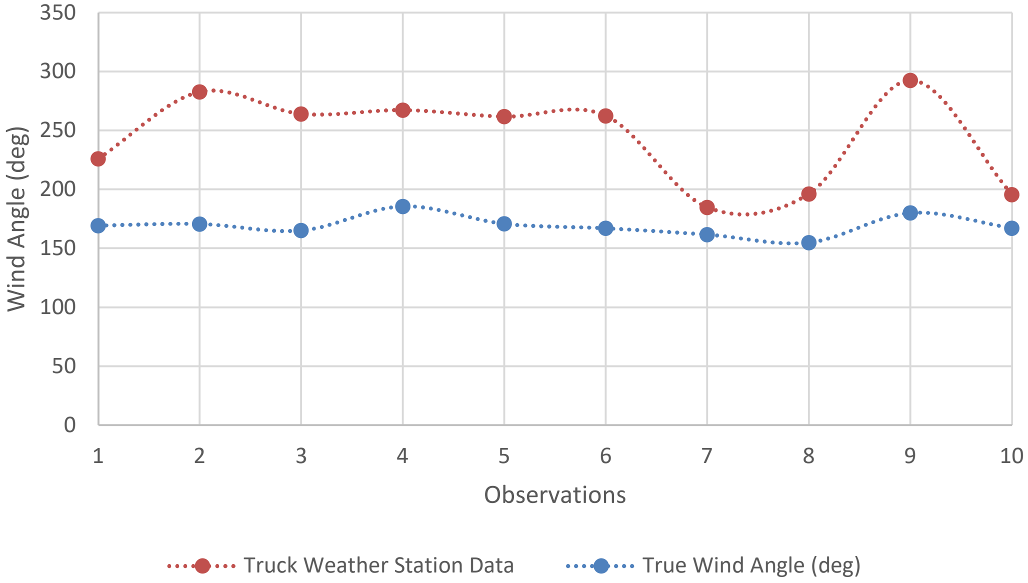


Figure E2: Velocity vector diagram

Furthermore, the wind measurements calibration result is shown in Figure E3. The true wind velocities are close to wind velocities measured by the weather station on the lead truck, but deviations are seen in the wind angles which were anticipated. The average errors after calibrating wind parameters were 5 km/h and 40 degrees for wind velocity and wind angle respectively. This was satisfactory because of the irregular pattern of the wind gusts that usually create a lot of noise in the analysis.



(a) Wind speed calibration



(b) Wind angle calibration

Figure E3: Wind measurements calibration

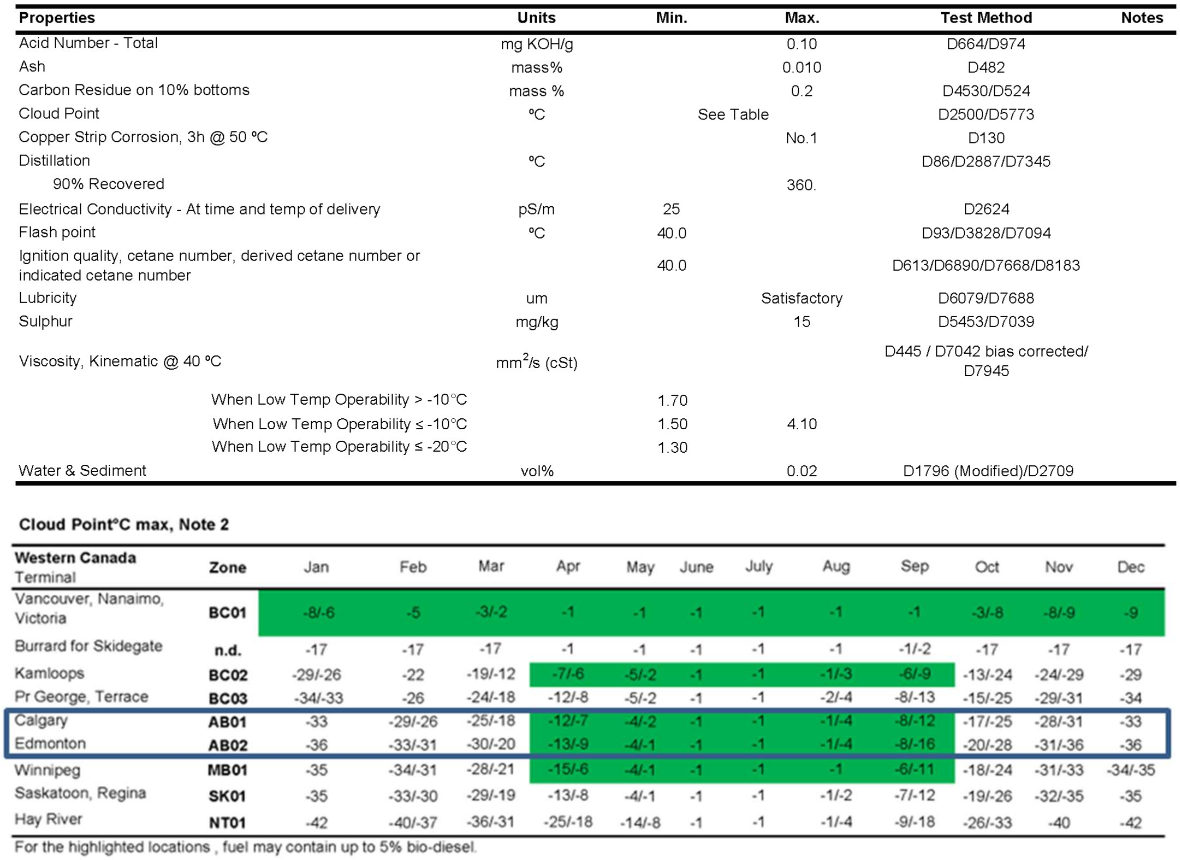
Appendix F: Fuel Properties

As shown in Figure F1, two vehicles refueling at an Esso station.

Figure F1: Two trucks were fueling at the Esso gas station used during trials

The fuel properties provided by Imperial Oil are detailed in Table F1.

Table F1: Fuel properties



Properties	Units	Min.	Max.	Test Method	Notes
Acid Number - Total	mg KOH/g		0.10	D664/D974	
Ash	mass%		0.010	D482	
Carbon Residue on 10% bottoms	mass %		0.2	D4530/D524	
Cloud Point	ºC	See Table		D2500/D5773	
Copper Strip Corrosion, 3h @ 50 ºC			No.1	D130	
Distillation	ºC			D86/D2887/D7345	
90% Recovered			360.		
Electrical Conductivity - At time and temp of delivery	pS/m	25		D2624	
Flash point	ºC	40.0		D93/D3828/D7094	
Ignition quality, cetane number, derived cetane number or indicated cetane number		40.0		D613/D6890/D7668/D8183	
Lubricity	um		Satisfactory	D6079/D7688	
Sulphur	mg/kg		15	D5453/D7039	
Viscosity, Kinematic @ 40 ºC	mm^2/s (cSt)			D445 / D7042 bias corrected/ D7945	
When Low Temp Operability > -10°C		1.70			
When Low Temp Operability ≤ -10°C		1.50	4.10		
When Low Temp Operability ≤ -20°C		1.30			
Water & Sediment	vol%		0.02	D1796 (Modified)/D2709	

Cloud Point°C max, Note 2

Western Canada Terminal	Zone	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Vancouver, Nanaimo, Victoria	**BC01**	-8/-6	-5	-3/-2	-1	-1	-1	-1	-1	-1	-3/-8	-8/-9	-9
Burrard for Skidegate	**n.d.**	-17	-17	-17	-1	-1	-1	-1	-1	-1/-2	-17	-17	-17
Kamloops	**BC02**	-29/-26	-22	-19/-12	-7/-6	-5/-2	-1	-1	-1/-3	-6/-9	-13/-24	-24/-29	-29
Pr George, Terrace	**BC03**	-34/-33	-26	-24/-18	-12/-8	-5/-2	-1	-1	-2/-4	-8/-13	-15/-25	-29/-31	-34
Calgary	**AB01**	-33	-29/-26	-25/-18	-12/-7	-4/-2	-1	-1	-1/-4	-8/-12	-17/-25	-28/-31	-33
Edmonton	**AB02**	-36	-33/-31	-30/-20	-13/-9	-4/-1	-1	-1	-1/-4	-8/-16	-20/-28	-31/-36	-36
Winnipeg	**MB01**	-35	-34/-31	-28/-21	-15/-6	-4/-1	-1	-1	-1	-6/-11	-18/-24	-31/-33	-34/-35
Saskatoon, Regina	**SK01**	-35	-33/-30	-29/-19	-13/-8	-4/-1	-1	-1	-1/-2	-7/-12	-19/-26	-32/-35	-35
Hay River	**NT01**	-42	-40/-37	-36/-31	-25/-18	-14/-8	-1	-1	-1/-4	-9/-18	-26/-33	-40	-42

For the highlighted locations , fuel may contain up to 5% bio-diesel.