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Impact Assessments of Automated Truck Platooning on Highway Traffic Flow and Adjacent Drivers

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16. Abstract

Automated Truck Platooning (ATP) enables a group of commercial trucks to move safely together with higher speeds and shorter headways between them. By assisting truck drivers and reducing human error, ATPs are expected to improve traffic safety. Since 2013, the performance of ATPs has been investigated through several research efforts that included data from selected locations across the United States. However, the success of ATPs in the future strongly depends on how other drivers on the road interact with them. A review of the literature in the field of ATP revealed that research has been more focused on the ATP and its drivers. There is little research on the driving behavior of other vehicles in the roadway interacting with ATPs. To address this issue, for this project, the NJIT research team investigated how vehicles surrounding the ATPs react to their presence by using a hybrid simulation framework integrating a driving simulator and a microscopic traffic simulator in real time.

Through extensive simulation experiments with human participants, it was discovered that when they approach an ATP, 1) most drivers maintain or increase their speed in order to pass the ATP as soon as possible; and 2) around one-third of drivers tend to stay in their lane and increase their speed in order to compete with the ATP and avoid being passed. When an ATP changes lanes to exit the highway, about one-half of drivers brake, with or without a lane change, in order to keep a safe distance from the ATP. Furthermore, in case a driver wants to take the exit on the right and the ATP is driving in the right lane, about one-half of the drivers brake to tailgate the ATP and then take the exit when the ATP has cleared; the other drivers increase their speed to either overtake or cut-in to the ATP. In addition, given that a driver wants to merge to the mainline from the right and the ATP is driving in the right lane, more than sixty percent of drivers decrease their speed and merge after the ATP has cleared the entrance area. This percentage is higher for larger platoons. It is also revealed that the drivers of the surrounding vehicles of the ATPs prefer the right lane of a three-lane roadway, rather the center or left lane, to be dedicated to ATPs.

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1 Introduction

1.1 Background

Automated Truck Platoons (ATP) enable a group of commercial trucks to move safely together with higher speed and shorter headways between them. Through assisting the drivers and reducing human errors, the ATP is expected to improve traffic safety. According to the research of Kuhn (2017) as cited by Lukuc et al. (2018), throughput of congested highways can increase by 6 to 8 percent if 30 to 50 percent of the trucks form two-truck automated truck platoons. Automated truck platooning can decrease fuel consumption by 5 to 20 percent and, as a result, lower the vehicle emissions of commercial fleets (Lukuc, Seymour, & Poe, 2018). Eastwood (2018) states that the lead and trailing trucks in platoons traveling at 53 mph will reduce their fuel usage by 8 percent and 14 percent, respectively. Based on an analysis of three million vehicle-miles of high-resolution truck data, the National Renewable Energy Laboratory (NREL) estimated that trucks can form platoons along about 65 percent of their paths and that will save 4 percent in fuel consumption (2018).

Development and implementation of ATP technology is being done through a sequence of stages. Lukuc et al. (2018) defined five levels of complementing ATP technology, as follows:

- In the first level, longitudinal movement, i.e. accelerating and braking, of the trailing trucks in the platoon will be automatically controlled however drivers will control the lateral movement, i.e. steering, of the trailing trucks. The technologies required for this level include radar, camera, Global Positioning System (GPS), Vehicle to Vehicle (V2V) communications, Cooperative Adaptive Cruise Control (CACC) and Forward Collision Avoidance and Mitigation (FCAM).
- In the second level, in addition to accelerating and braking, the steering will also be done automatically. However, drivers will continue to monitor the performance of the trucks.
- The third level is called conditional automation. In this level, the supervision of the driver is not required during simple driving conditions.
- The fourth and fifth levels are called high automation and full automation, respectively. In these two levels, the driver does not take part in any driving activities (Lukuc, Seymour, & Poe, 2018).

1.2 Problem Statement

Truck platoons equipped with the first two levels of ATP technology are currently being tested in the United States. Sixteen states[1] have supported testing of truck platoons on their highways. Since 2013, the performance of ATPs has been investigated by seven projects encompassing thirteen different locations nationwide (Lukuc, Seymour, & Poe, 2018).

Eastwood (2018) states that the connectivity technologies such as Wi-Fi, 4G, LTE and 5G are maturing to ensure V2V and Vehicle to Infrastructure (V2I) communications for connected and autonomous vehicles (CAV) in the near future. In addition to the technological requirements, legal and administrative

[1] The states of Virginia, North Carolina, South Carolina, Georgia, Florida, Ohio, Michigan, Tennessee, Arkansas, Texas, New Mexico, Arizona, Utah, California, Nevada, Oregon.

procedures as well as acceptance and trust in ATP technology by drivers are among the potential challenges for the adoption of ATP technology by logistics companies (Lukuc, Seymour, & Poe, 2018).

A literature review on automated truck platoon (ATP) showed that most research on ATPs have focused on the performance of the automated truck platoons and there is little research on the driving behavior of vehicles surrounding the ATP. In September 2018, the USDOT released a broad agency announcement for the early deployment and evaluation of automated truck platooning. One of the specific research questions was how the behavior of other road users (with regard to entry/exit points, visibility, etc.) is affected by the truck platoon (Green Car Congress, 2018). This question is additional proof of the lack of research on the driving behavior of vehicles surrounding the ATP.

1.3 Research Approach

In this project, the NJIT research team investigated how the vehicles surrounding the ATP react to the presence of an automated truck platoon (ATP) on highways. The research was done using a high-fidelity driving simulator. To increase the reality of the simulation environment, the driving simulator is connected to a state-of-the-art multimodal traffic simulator software package. The traffic simulator software is used to control the behavior of both the truck platoon and any ambient traffic. The following objectives were accomplished in this project:

- To review current research on driving behavior of the ATP drivers and the vehicles surrounding the ATPs
- To build a high-fidelity simulation environment for conducting the tests
- To conduct the experiments
- To summarize the findings from the experiments
- To identify challenges that are discovered during the project

The rest of this report is organized as follows:

Chapter 2: Relevant research efforts on the driving behavior of ATP drivers and the vehicles surrounding the ATPs are reviewed.

Chapter 3: Research methodology including the simulation model, design of the experiments (scenarios) and the questionnaire are described.

Chapter 4: The results of the questionnaire are presented and analyzed.

Chapter 5: The results and conclusions are presented and challenges for additional research are explored.

2 Literature Review

This chapter briefly reviews previous research in the field of automated truck platoons (ATP). Most of the literature in this area has been focused on the ATPs and their drivers and there is little research on the behavior of the vehicles surrounding the ATPs.

Lee, Oh and Hong (2018) studied the lane changing behavior of regular vehicles (RV) in the presence of autonomous vehicle (AV) platoons, using a driving simulator. The simulation environment was a 3-km freeway with three lanes in each direction and a posted speed limit of 100 km/hr. The market penetration rate for the AVs varied between 0 and 50 percent. AVs were set to drive in the left and right lanes in platoons with speed equal to 100 km/hr speed in combination with RVs. The platoon size varied between four and ten vehicles and the headway between platoon vehicles was set to four meters. Thirty individuals participated in the test as subject drivers. They started in the center lane and were instructed to change lane into the platoon lanes when requested if they find an appropriate gap. They could cancel the lane change if they could not find an appropriate gap. Cancelling the lane change or collision with other vehicles were both regarded as lane change failures. The results of ANOVA test on the outputs showed that increasing market penetration rate of the AVs lead to longer times to find an acceptable gap to change lanes into the platoon lanes. While executing the lane change, steering magnitude and angular velocity increase with increasing market penetration rate of the AVs. Using a binomial logistic regression model, the researchers found that the probability of lane change failure is directly related to the average speed of the subject vehicle and inversely related to the AVs market penetration rate, the age of the driver and the driver being female.

Gouy et al. (2014) studied the headways of regular vehicles (RV) when driving adjacent to an automated truck platoon (ATP). The study was done using a driving simulator. The experiment environment was a simulated three-lane left-hand motorway with the speed limit of 70 mph (112.6 km/hr). The ATPs were driving on the closest lane to the entrance and exit ramps, the left lane in left-hand traffic, at speeds of 90 km/hr. The headway between the trucks of the same platoon was 0.3 seconds in short headway conditions and 1.4 seconds in long headway conditions. The participants were instructed to follow a lead vehicle. The lead vehicle was programmed to drive at 93 km/hr in the center lane. The experiment for each individual consisted of three fifteen-minute intervals plus a one-minute warm-up period for each interval. Thirty participants were divided into two groups with an equal number of members. The first group drove three scenarios: without platoon, short-headway platoon and long-headway platoon. For the second group the order of the last two intervals was reversed to control the effects of order. The results of the t-test on the outputs showed that driving in the lane next to a truck platoon with short-headways caused a significant lower mean headway between the subject vehicle and the lead vehicle. The difference was 0.12 seconds that at 93 km/h is equal to 3.1 m. The minimum headway was also significantly lower. The difference was 0.16 seconds. The minimum headway in the short-headway platoon condition was 1.0 second. The drivers also had significantly higher proportion of time with less than one second of headway in that case. A significant difference was also found on the standard deviation of lateral position (SDLP). The mean of the (SDLP) was 0.18 m in the long-headway platoon and 0.17 m in the short-headway platoon showing that drivers increase their effort to be more alert when driving next to a short-headway ATP.

Heikoop et al. (2017) studied the workload and stress of automated platoon drivers in a driving simulator experiment. The subject vehicle's driving maneuvers were fully automated. The drivers' responsibility was defined in three levels: 1) Monitor the road and just intervene in critical situations; 2) Perform any additional activity they want such as reading and eating; and 3) In addition to task 1, detect cars of a specific color. Twenty-two participants drove forty minutes under each task level in a five-vehicle platoon with speeds of 120 km/hr and 0.3 seconds headway. The results of the Dundee stress state questionnaire (DSSQ) filled out by the drivers show that their level of stress was significantly lower in task 2.

Heikoop et al. (2018) investigated the situation awareness of automated platoon drivers in a similar experiment. Thirty-three individuals participated in this experiment. The drivers were instructed to monitor the road and just intervene in critical situations and to state out loud what they were thinking about every two minutes. Three levels of mental effort were being experienced: 1) No task; 2) Voluntarily repeat the second last letter named by a narrator in a sequence of letters; and 3) Mandatorily repeat the second last letter. The results showed that the higher level of mental tasks significantly lowered the situation awareness of the drivers.

Zheng et al. (2015) quantitatively evaluated the mental stress level of automated truck drivers while following another truck at close distance. The experiment was done using a driving simulator. Ten participants drove under four different scenarios for a time period of 5 to 8 minutes per scenario. The scenarios were: manual driving with a following distance of 20 to 30 m and three automated driving with a set following distance of 12, 8 and 4 m respectively. The lead truck was driving at 80 km/hr and at a random point at the end of each part of the experiment it decelerated to 30 km/h in 2.5 minutes. In the manual driving condition, the participants had to adjust their speed to prevent collision. In the automated driving condition, the speed was adjusted automatically. The results show that the driver's stress significantly increased when driving with a shorter headway. In addition, during the automated driving conditions, the sudden deceleration of the lead truck caused a drastic increase of the stress level of the subject drivers.

Reviewing the literature on automated truck platoons (ATP) showed that there is little research on the driving behavior of vehicles surrounding the ATP. The success of ATPs in the future strongly depends on how other drivers on the road interact with them. As a result, it is required to further investigate the interaction between other drivers with ATPs.

3 Methodology

3.1 Overview

The objective of the research methodology was to determine how drivers behave in the presence of automated truck platoons (ATP) on a typical highway. Four different scenarios were considered: the first two scenarios considered a driver entering and exiting a roadway with an ATP in an adjacent lane; the latter two scenarios considered a driver traveling through an interchange while an ATP is entering or exiting the roadway. Platoons of three different lengths: five, seven and ten trucks; were considered.

Two tools were used in the methodology: 1) a simulation model was created using the NJIT driving simulator (DS) coupled with the PTV VISSIM traffic simulation software; and 2) a sixteen-question written questionnaire was prepared. Twelve drivers were recruited for the study and each driver took part in eight actual DS tests (four scenarios by two platoon lengths) and answered questions about twelve theoretical tests (four scenarios by three platoon lengths). The questionnaire was only answered after the driver had completed all of the DS tests.

For each DS test for each driver, the vehicle acceleration and/or deceleration rates was continuously tracked throughout the simulation. The sample size for both the DS tests and the questionnaires in this initial research were too small to draw significant conclusions. However, a review of both the quantitative and qualitative data collected provided insight into driver behavior as well as guidance for future research.

The remainder of this section is divided into three parts. The first part provides a discussion of the driver simulation model. The second part describes the tests that were conducted and provides a summary of the acceleration and deceleration data collected as well as some initial conclusions. The final part describes the development of the questionnaire, the results, and some additional conclusions.

3.2 Simulation model development

As discussed in the previous section, the current research was done using a high-fidelity driving simulator shown in **Figure 1**. To conduct the experiments using the driving simulator (DS), a simulation environment was built using the Internet Scene Assembler (ISA) software.

Figure 1: NJIT Driving Simulator (DS) System

The environment is a flat and straight highway with three lanes in each direction. The highway, shown in **Figure 2**, consists of a 2-km basic segment at the start, a 1.1-km off-ramp segment, a 1.1-km on-ramp segment, and a 2-km basic segment at the end. The off-ramp and on-ramp are on the right and connect the highway to another road that is aligned perpendicular to and six meters above the highway. The speed limit is 75 mph on the highway and 45 mph on the ramps.

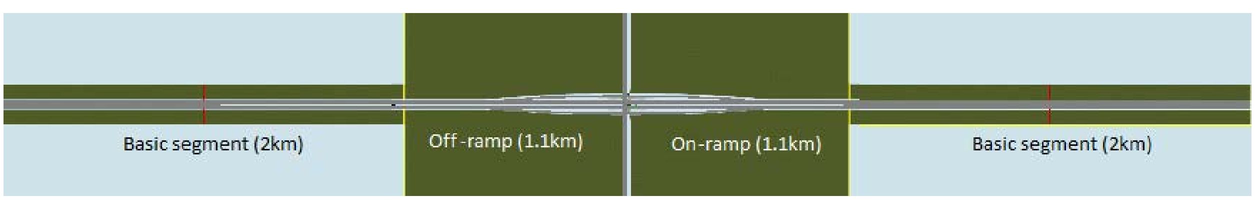
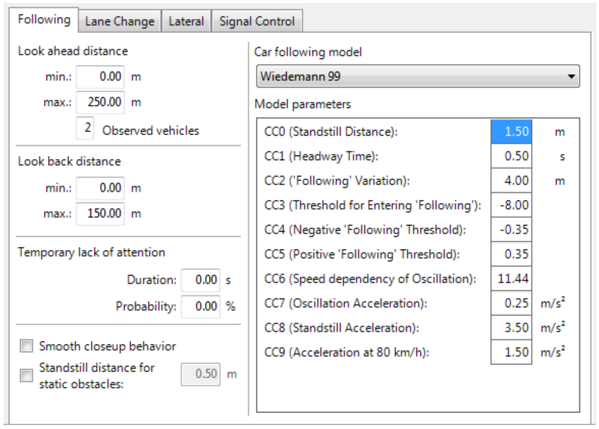
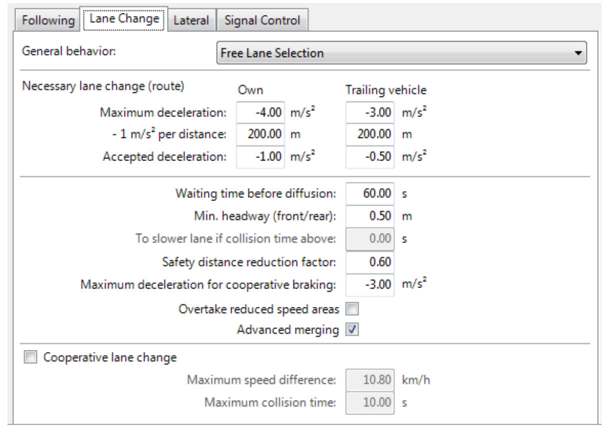


Figure 2: Simulation environment

Due to the limitations of the DS system, only the automated truck platoons (ATP) are simulated and no other traffic is modeled in the environment. In order to make the ATP driving behavior more realistic, the DS is connected to the VISSIM multimodal traffic simulation software so that VISSIM controls the driving behavior of the ATP with its embedded driving behavior model. The longitudinal (vehicle following) and lane selection (lane change) driving behavior of the ATP are shown in **Figure 3**. The driving behavior model embedded in VISSIM is based on the Wiedemann driving behavior model (PTV AG, 2011).



(a) Longitudinal behavior



(b) Lane selection behavior

Figure 3: Driving behavior of the ATP

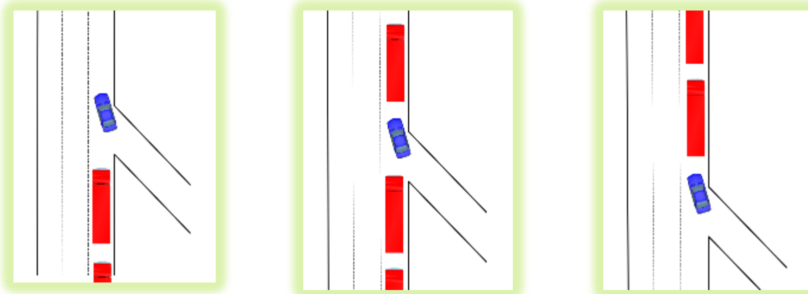
The simulation roadway environment shown earlier was precisely replicated in VISSIM 5.40 and the ATP vehicles were defined. At intervals of 0.1 seconds, the position of the ATP vehicles in VISSIM was sent to the DS and the position of the subject vehicle in the DS was sent to VISSIM. This continuous exchange of data between the DS and VISSIM allows both the subject vehicle and the ATP to react to the driving behavior of each other.

3.3 Experiments design

Four different scenarios were designed and are described in this section. Three different platoon sizes were considered for each scenario, for a total of twelve different tests. Each participant took all of the tests in random order. Prior to each test, the instructions were read to the participant, however information on the maneuvers of the ATP were not included in the instructions. As a result, the participant was not aware of the situation that he/she would encounter. During the tests, quantitative measures of the subject vehicle: acceleration, speed, and location coordinates, were collected at 1/10 second intervals for post-processing and analysis. A continuous summary of the quantitative data for all participants each of the twelve tests is included in **Appendix B**.

3.3.1 Scenario 1

In this scenario, the interaction of the subject driver with the ATP during the merge maneuver was investigated. The right lane of the highway is exclusively dedicated to the ATP and the ATP drives at 65 mph with 0.5 seconds of headway between the trucks. The subject driver starts from the on-ramp and merges on to the highway with one of the alternatives that is illustrated in **Figure 4**. The driver may merge before the first vehicle in the ATP as shown in **Figure 4(a)**; between two vehicles in the ATP as shown in **Figure 4(b)**; or after the last vehicle in the ATP as shown in **Figure 4(c)**. An acceleration lane of 90 m and a merging area of 60 m are provided. Platoon sizes of five, seven and ten trucks were tested. A subject driver taking part in Scenario 1 is shown in **Figure 5**.



(a) (b) (c)

Figure 4: Scenario 1 (Three Merge Alternatives)

Figure 5: Participant Taking Scenario 1

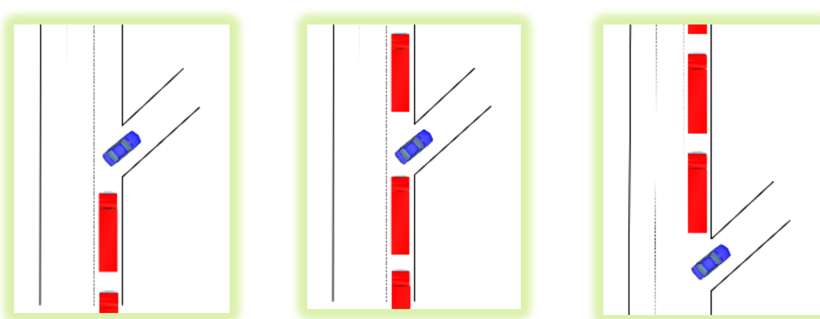
The acceleration and deceleration rates for each of the twelve drivers was continuously tracked and are summarized in **Figure 17**, **Figure 18** and **Figure 19** for platoon sizes of five, seven and ten trucks, respectively. The figures show that most drivers behaved similarly regardless of the platoon size. Safe, hard, and maximum acceleration/braking rates were defined as 2.0/-2.0 m/s; 4.0/-4.0 m/s; and 6.0/-6.0 m/s, respectively. The figures were reviewed to count the number of times that any driver exceeded these ranges. A single driver in a test could be responsible for multiple occurrences of both hard acceleration and braking. The data for Scenario 1 is summarized in **Table 1**. As seen in the table, drivers are much more likely to brake to merge onto the highway after the last vehicle in the platoon than accelerate hard to merge before the first vehicle regardless of the platoon size.

Table 1: Summary of Scenario 1 Tests

Scenario 1 Observations with Acceleration Rates Greater Than:								
2.0 m/s² (Safe)			4.0 m/s² (Hard)			6.0 m/s² (Maximum)		
Platoon Size			Platoon Size			Platoon Size		
5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs
0	5	0	1	1	2	0	0	0
Scenario 1 Observations with Deceleration Rates Greater Than:								
2.0 m/s² (Safe)			4.0 m/s² (Hard)			6.0 m/s² (Maximum)		
Platoon Size			Platoon Size			Platoon Size		
5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs
1	4	3	3	4	0	2	4	4

3.3.2 Scenario 2

In this scenario, the interaction of the subject driver with the ATP during the diverge or exit maneuver was investigated. The right lane of the highway is exclusively dedicated to the ATP and the ATP drives at 65 mph with 0.5 seconds of headway between the trucks. The subject driver starts from the center lane of the highway and takes the off-ramp to exit with one of the alternatives that is illustrated in **Figure** 6. The driver may exit before the first vehicle in the ATP as shown in **Figure 6(a)**; between two vehicles in the ATP as shown in **Figure 6(b)**; or after the last vehicle in the ATP as shown in **Figure 6(c)**. Platoon sizes of five, seven and ten trucks were tested. A subject driver taking part in Scenario 2 is shown in **Figure 7**.



(a) (b) (c)

Figure 6: Scenario 2 (Three Exit Alternatives)

Figure 7: Participant Taking Scenario 2

The acceleration and deceleration rates for each of the twelve drivers was continuously tracked and are summarized in **Figure 20**, **Figure 21** and **Figure 22** for platoon sizes of five, seven and ten trucks, respectively. The figures show that most drivers did not behave similarly for small platoons (five vehicles) versus medium and large platoons (seven and ten vehicles). As stated in the previous section, safe, hard, and maximum acceleration/braking rates were defined as 2.0/-2.0 m/s; 4.0/-4.0 m/s; and 6.0/-6.0 m/s, respectively and the figures were reviewed to count the number of times that any driver exceeded these ranges. A single driver in a test could be responsible for multiple occurrences of both hard acceleration and braking. The data for Scenario 2 is summarized in **Table 2**. As seen in the table, drivers are as likely to brake hard to merge into the right lane after the last vehicle in the platoon as they are to accelerate hard to merge before the first vehicle in the case of the small platoon. Drivers however are far more likely to brake hard rather than accelerate for both the medium and large platoons.

Table 2: Summary of Scenario 2 Tests

Scenario 2 Observations with Acceleration Rates Greater Than:								
2.0 m/s2 (Safe)			4.0 m/s2 (Hard)			6.0 m/s2 (Maximum)		
Platoon Size			Platoon Size			Platoon Size		
5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs
0	0	0	0	0	0	0	0	0
Scenario 2 Observations with Deceleration Rates Greater Than:								
2.0 m/s2 (Safe)			4.0 m/s2 (Hard)			6.0 m/s2 (Maximum)		
Platoon Size			Platoon Size			Platoon Size		
5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs
4	8	7	4	6	4	0	4	4

3.3.3 Scenario 3

In this scenario, the interaction of the subject driver with the ATP when the ATP merges to the highway and changes lanes was investigated. The left lane of the highway is exclusively dedicated to the ATP and the ATP drives at 65 mph with 0.5 seconds of headway between the trucks. The subject vehicle starts from the center lane on the highway, while the ATP starts from the on-ramp, merges on to the highway and changes lanes to the left lane as shown in **Figure 8**. Platoon sizes of five, seven and ten trucks were tested. A subject driver taking part in Scenario 3 is shown in **Figure 9.**

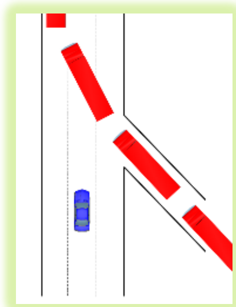


Figure 8: Scenario 3

Figure 9: Participant Taking Scenario 3

The acceleration and deceleration rates for each of the twelve drivers was continuously tracked and are summarized in **Figure 23**, **Figure 24** and **Figure 25** for platoon sizes of five, seven and ten trucks, respectively. The figures show that most drivers behaved similarly regardless of the platoon size. Safe, hard, and maximum acceleration/braking rates were defined as 2.0/-2.0 m/s; 4.0/-4.0 m/s; and 6.0/-6.0 m/s, respectively. The figures were reviewed to count the number of times that any driver exceeded these ranges. A single driver in a test could be responsible for multiple occurrences of both hard acceleration and braking. The data for Scenario 3 is summarized in **Table 3**. As seen in the table, drivers are more likely to brake safe or hard to avoid a truck platoon that is merging onto the highway and this decision was generally consistent regardless of the platoon size.

Table 3: Summary of Scenario 3 Tests

Scenario 3 Observations with Acceleration Rates Greater Than:								
2.0 m/s2 (Safe)			4.0 m/s2 (Hard)			6.0 m/s2 (Maximum)		
Platoon Size			Platoon Size			Platoon Size		
5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs
0	0	0	0	0	0	0	0	0
Scenario 3 Observations with Deceleration Rates Greater Than:								
2.0 m/s2 (Safe)			4.0 m/s2 (Hard)			6.0 m/s2 (Maximum)		
Platoon Size			Platoon Size			Platoon Size		
5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs
1	3	3	3	1	3	0	1	0

3.3.4 Scenario 4

In this scenario, the interaction of the subject driver with the ATP when the ATP changes lane to exit the highway was investigated. The left lane of the highway is exclusively dedicated to the ATP and the ATP drives at 65 mph with 0.5 seconds of headway between the trucks. The subject vehicle starts from the center lane on the highway. The ATP starts from the left lane of the highway, changes lanes to the right and takes the off-ramp as shown in **Figure 10**. Platoon sizes of five, seven, and ten trucks were tested. A subject driver taking part in Scenario 4 is shown in **Figure 11.**

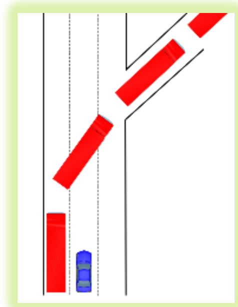


Figure 10: Scenario 4

Figure 11: Participant Taking Scenario 4

The acceleration and deceleration rates for each of the twelve drivers was continuously tracked and are summarized in **Figure 26**, **Figure 27** and **Figure 28** for platoon sizes of five, seven and ten trucks, respectively. It is difficult to draw conclusions from the figures as most drivers did not behave similarly for medium platoons (seven vehicles) compared to both small and large platoons (five and ten vehicles). As stated in the previous sections, safe, hard, and maximum acceleration/braking rates were defined as 2.0/-2.0 m/s; 4.0/-4.0 m/s; and 6.0/-6.0 m/s, respectively and the figures were reviewed to count the number of times that any driver exceeded these ranges. A single driver in a test could be responsible for multiple occurrences of both hard acceleration and braking. The data for Scenario 4 is summarized in **Table 4**. As seen in the table, the drivers are likely to brake safe in order to avoid the truck platoon that is changing the lane to take the exit ramp.

Table 4: Summary of Scenario 4 Tests

Scenario 4 Observations with Acceleration Rates Greater Than:								
2.0 m/s2 (Safe)			4.0 m/s2 (Hard)			6.0 m/s2 (Maximum)		
Platoon Size			Platoon Size			Platoon Size		
5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs
0	0	0	0	0	0	0	0	0
Scenario 4 Observations with Deceleration Rates Greater Than:								
2.0 m/s2 (Safe)			4.0 m/s2 (Hard)			6.0 m/s2 (Maximum)		
Platoon Size			Platoon Size			Platoon Size		
5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs	5 Vehs	7 Vehs	10 Vehs
2	6	2	0	3	0	0	2	1

3.4 Questionnaire

After all DS tests were taken, each participant filled out a questionnaire on the maneuvers he/she took in the four different scenarios. The questionnaire was designed by the project team for qualitative analysis of the driving behavior of the participants. The individual questions that comprise the questionnaire are discussed in this section and the complete questionnaire is contained in **Appendix A**.

The first two questions, shown in **Figure 12**, investigated the behavior of the driver if he/she approached an ATP or vice-versa. The behavior was questioned for two different ATP sizes and relative lateral positions of the ATP to the subject vehicle. The participant described his/her driving behavior by selecting an alternative of lane selection behavior and longitudinal behavior.

Q1. What was your primary driving maneuver when you approached a truck platoon (Check all that apply)

Platoon Length	Platoon Location	Stay in lane	Change lane	Maintain speed	Accelerate	Brake
Short (5 Trucks)	On the same lane					
	On your right					
	On your left					
Long (10 Trucks)	On the same lane					
	On your right					
	On your left					

Q2. What was your primary driving maneuver when a platoon approached you (Check all that apply)

Platoon Length	Platoon Location	Stay in lane	Change lane	Maintain speed	Accelerate	Brake
Short (5 Trucks)	On the same lane					
	On your right					
	On your left					
Long (10 Trucks)	On the same lane					
	On your right					
	On your left					

Figure 12: Questions 1 and 2

The third question, shown in **Figure 13**, asked how the driver reacted when the ATP changed lane to take the exit. The behavior is questioned for two different ATP sizes. Similar to the previous questions, the participant describes his/her driving behavior by selecting an alternative of lane selection behavior and longitudinal behavior.

Q3. What was your primary driving maneuver if a platoon changes lane to take the exit ramp when you drove forward around the ramp area (Check all that apply).

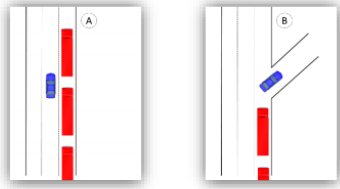
Platoon Length	Stay in lane	Change lane	Maintain speed	Accelerate	Brake
Short (5 Trucks)					
Long (10 Trucks)					

Figure 13: Question 3

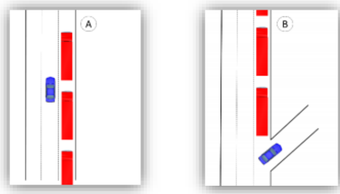
The fourth question, shown in **Figure 14**, asked the behavior of the driver if he/she wanted to exit from the mainline and the ATP is in the right lane. The behavior is questioned for two different ATP sizes. The choices for describing the driving behavior in this question are: Accelerate to pass the ATP; Brake to tailgate the ATP; Cut-in between two vehicles in the ATP; and Do nothing special.

Q4. What was your primary driving maneuver if a platoon existed on the right-most lane when you attempted to take the exit ramp.

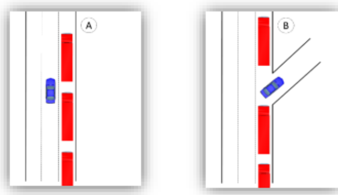
[1] Accelerate to pass the platoon: By accelerating, you overtook the platoon and drove through the ramp before the platoon reaches the ramp.



[2] Brake to tailgate the platoon: You reduced your speed to let the platoon pass you. Then you changed lane and followed the platoon. You drove through the exit ramp when you reached that.



[3] Cut-in to the platoon: While the platoon was passing the exit ramp, you drove between the trucks and took the exit ramp.



[4] Do nothing special:

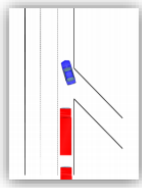
Platoon Length	[1]	[2]	[3]	[4]
Short (5 Trucks)				
Long (10 Trucks)				

Figure 14: Question 4

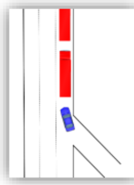
The fifth question, shown in **Figure 15**, asks the behavior of the driver if he/she wants to merge into the mainline and the ATP is in the right lane. The behavior is questioned for two different ATP sizes. The choices for describing the driving behavior in this question are: Accelerate to pass the ATP; Brake to tailgate the ATP; Cut-in between two vehicles in the ATP; and Do nothing special.

Q5. What was your primary driving maneuver if a platoon existed on the right-most lane when you attempted to merge into the mainline.

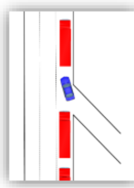
[1] Accelerate to pass the platoon: By accelerating, you reached the merging point ahead of the platoon and drove into the freeway.



[2] Brake to tailgate the platoon: By reducing your speed, you let the platoon pass the merging point and then you entered the freeway.



[3] Cut-in to the platoon: While the platoon was at the merging point, you drove between the trucks and entered the freeway.



[4] Do nothing special.

Platoon Length	[1]	[2]	[3]	[4]
Short (5 Trucks)				
Long (10 Trucks)				

Figure 15: Question 5

Given two different sizes of ATPs, the final question, shown in **Figure 16**, asks which of the three lanes: left, center or right, which the participants prefer to be dedicated to the ATPs.

Q6. If a lane is necessarily dedicated for automated truck platooning, which lane do you prefer?

Platoon Length	Left-most Lane	Middle-lane	Right-most lane
Short (5 Trucks)			
Long (10 Trucks)			

Figure 16: Question 6

4 Results and Findings

4.1 Subject drivers

Twelve licensed drivers were hired by the project team to participate in the experiments as the drivers of the subject vehicle. All drivers did not have any health problems that affected their driving behavior. Nine drivers were male and three were female. Ten drivers were thirty years old or younger. One third had between one and five years of driving experience and more than half had between five and fifteen years of driving experience. Half of the participants drive on a daily basis and only two drivers had been involved in crashes in the past three years. The complete characteristics of the subject drivers are shown in **Table 5.**

Table 5: Characteristics of Subject Drivers

Characteristic	Distribution of the subject drivers			
Gender	Male		Female	
	9 (75%)		3 (25%)	
Age [years]	Less than 25	26 to 30	31 to 35	Greater than 36
	5 (42%)	5 (42%)	2 (17%)	0 (0%)
Driving experience [years]	Less than 1	Between 1 and 5	Between 5 and 15	Greater than 15
	1 (8%)	4 (33%)	7 (58%)	0 (0%)
Driving frequency	Daily	Once a week	Occasionally	
	6 (50%)	1 (8%)	5 (42%)	
Crash experience in the past three years	Yes		No	
	2 (17%)		10 (83%)	

All drivers conducted a warm-up driving session for at least ten minutes to get used to driving the simulator through a virtual environment. The environment for the warm-up period was different from the test environment. Warm-up sessions took around fifteen minutes on average and the tests started when the driver stated his/her readiness. Including warm-up period, the whole experiment for an individual took about ninety minutes. After the driving tests, the participants filled out the questionnaire.

4.2 Analysis

As discussed in the previous section, after all driving experiments were taken, the participants filled out a questionnaire on their preferred driving maneuvers for different situations. The data obtained from the questionnaire are presented and discussed in the following sections.

4.2.1 Driving behavior when approaching the ATP

The first question in the questionnaire dealt with driving behavior when approaching an automated truck platoon (ATP). In general, the responses for short and long platoons were identical except for approaching a platoon on their right. Only one of twelve drivers would change lanes for a short platoon while three of twelve drivers would change lanes for a long platoon. In general, most drivers preferred to stay in their lane and maintain speed or accelerate to pass the platoon if the platoon is on either their left or right. Between nine and eleven of the twelve drivers preferred to stay in their lane for both short and long platoons; and between ten and eleven of the twelve drivers preferred to maintain speed or accelerate. Most drivers, eight of twelve, preferred to change lanes if a short or long platoon was in their lane; and most drivers, again eight of twelve, preferred to maintain speed or accelerate to pass the platoon regardless of the platoon length. Between one and four of the twelve drivers selected to reduce speed regardless of the length of the truck platoon or the lane it was in. The complete results for Question 1 are summarized in **Table 6** below.

Table 6: Preferred driving maneuver – driver approaching ATP in the same lane, on your right or on your left

Platoon Length	Platoon Location	Lane Selection Behavior		Driving Behavior		
		Stay in Lane	Change Lane	Maintain Speed	Accelerate	Brake
Short (5 Trucks)	In the same lane	4 (33%)	8 (67%)	1 (8%)	7 (58%)	4 (33%)
	On your right	11 (92%)	1 (8%)	3 (25%)	7 (58%)	2 (17%)
	On your left	11 (92%)	1 (8%)	6 (50%)	5 (42%)	1 (8%)
	All locations	26 72%)	10 (28%)	10 (28%)	19 (53%)	7 (19%)
Long (10 Trucks)	In the same lane	4 (33%)	8 (67%)	1 (8%)	7 (58%)	4 (33%)
	On your right	9 (75%)	3 (25%)	3 (25%)	7 (58%)	2 (17%)
	On your left	11 (92%)	1 (8%)	6 (50%)	5 (42%)	1 (8%)
	All locations	24 (67%)	12 (33%)	10 (28%)	19 (53%)	7 (19%)
All Platoons	In the same lane	8 (33%)	16 (67%)	2 (8%)	14 (58%)	8 (33%)
	On your right	20 (83%)	4 (17%)	6 (25%)	14 (58%)	4 (17%)
	On your left	22 (92%)	2 (8%)	12 (50%)	10 (42%)	2 (8%)
	All locations	50 (69%)	22 (31%)	20 (28%)	38 (53%)	14 (19%)

4.2.2 Driving behavior when the ATP approaches the vehicle

The second question in the questionnaire dealt with driving behavior when being approached by an automated truck platoon (ATP). In general, the responses for short and long platoons were identical with only one minor exception. Only one of twelve drivers would change lanes for a short platoon on their left while two of twelve drivers would change lanes for a long platoon on their left. In general, most drivers preferred to stay in their lane if the platoon is on either their left or right. Either ten or eleven of the twelve drivers preferred to stay in their lane for both short and long platoons. Half of the drivers, six of twelve, preferred to stay in their lane and accelerate if a short or long platoon was in their lane. In addition, most drivers preferred to either maintain speed or accelerate to avoid the platoon regardless of the platoon length. Only between three and five of the twelve drivers selected to reduce speed, with or without a lane change maneuver, regardless of the length of the truck platoon or the lane it was in. The complete results for Question 2 are summarized in **Table 7** below.

Table 7: Preferred driving maneuver – ATP approaches driver in same lane, on its right or on its left

Platoon Length	Platoon Location	Lane Selection Behavior		Driving Behavior		
		Stay in Lane	Change Lane	Maintain Speed	Accelerate	Brake
Short (5 Trucks)	In the same lane	6 (50%)	6 (50%)	1 (8%)	6 (50%)	5 (42%)
	On your right	10 (83%)	2 (17%)	6 (50%)	3 (25%)	3 (25%)
	On your left	11 (92%)	1 (8%)	6 (50%)	3 (25%)	3 (25%)
	All locations	27 (75%)	9 (25%)	13 (36%)	12 (33%)	11 (31%)
Long (10 Trucks)	In the same lane	6 (50%)	6 (50%)	2 (17%)	6 (50%)	4 (33%)
	On your right	10 (83%)	2 (17%)	5 (42%)	4 (33%)	3 (25%)
	On your left	10 (83%)	2 (17%)	6 (50%)	3 (25%)	3 (25%)
	All locations	26 (72%)	10 (28%)	13 (36%)	13 (36%)	10 (28%)
All Platoons	In the same lane	12 (50%)	12 (50%)	3 (13%)	12 (50%)	9 (38%)
	On your right	20 (83%)	4 (17%)	11 (46%)	7 (29%)	6 (25%)
	On your left	21 (88%)	3 (13%)	12 (50%)	6 (25%)	6 (25%)
	All locations	53 (74%)	19 (26%)	26 (36%)	25 (35%)	21 (29%)

Based on the detailed analyses above, it can be concluded that generally when the ATP approaches the vehicles, around 30% of the drivers tend to stay in lane and increase their speed. In other words they compete with the ATP.

4.2.3 Driving behavior when the ATP changes lane to take the exit

Approximately half of all drivers preferred to stay in their lane and brake when the ATP changed lanes in order to access the exit ramp. This percentage was higher for short ATPs compared to long ATPs. The length of the platoon did not appear to have much impact as their were no clear second preferences for either platoon length. The complete survey response is shown in **Table 8**.

Table 8: Preferred car driving maneuver – ATP changes lane to exit

Car Driving Maneuver	Short ATP (5 vehicles)	Long ATP (10 vehicles)	All ATPs
Stay in lane – maintain speed	1 (8%)	2 (17%)	3 (13%)
Stay in lane – accelerate	1 (8%)	1 (8%)	2 (8%)
Stay in lane – brake	7 (58%)	5 (42%)	12 (50%)
Change lane – maintain speed	0 (0%)	1 (8%)	1 (4%)
Change lane – accelerate	2 (17%)	1 (8%)	3 (13%)
Change lane – brake	1 (8%)	2 (17%)	3 (13%)
Total	12 (100%)	12 (100%)	24 (100%)

4.2.4 Exit and merging driving behavior in conflict with the ATP

The majority of drivers preferred to brake to tailgate the ATP in order to access the exit ramp. This percentage was the same (six of twelve drivers or 50%) for both short ATPs and long ATPs. The length of the platoon directly impacted the second preference. For short ATPs, more aggressive drivers chose to accelerate to pass the platoon; for long ATPs, these drivers chose to accelerate to cut-in to the platoon. The complete survey response is shown in **Table 9**.

Table 9: Preferred car driving maneuver to exit - ATP is in the right lane

Car Driving Maneuver	Short ATP (5 vehicles)	Long ATP (10 vehicles)	All ATPs
Accelerate to pass the platoon	5 (42%)	2 (17%)	7 (29%)
Brake to tailgate the platoon	6 (50%)	6 (50%)	12 (50%)
Cut-In to the platoon	1 (8%)	4 (33%)	5 (21%)
Do Nothing special	0 (0%)	0 (0%)	0 (0%)
Total	12 (100%)	12 (100%)	24 (100%)

The majority of drivers also preferred to brake to tailgate the ATP in order to merge onto the mainline. This percentage was greater than 50% for both short ATPs and long ATPs. The length of the platoon again directly impacted the second preference. For short ATPs, more aggressive drivers chose to accelerate to pass the platoon; for long ATPs, only one of twelve drivers chose to accelerate to pass the platoon. The complete survey response is shown in **Table 10**.

Table 10: Preferred car driving maneuver to merge - ATP is in the right lane

Car Driving Maneuver	Short ATP (5 vehicles)	Long ATP (10 vehicles)	All ATPs
Accelerate to pass the platoon	3 (25%)	1 (8%)	4 (17%)
Brake to tailgate the platoon	7 (58%)	9 (75%)	16 (67%)
Cut-In to the platoon	2 (17%)	2 (17%)	4 (17%)
Do Nothing special	0 (0%)	0 (0%)	0 (0%)
Total	12 (100%)	12 (100%)	24 (100%)

4.2.5 Preferred lanes for the ATPs

The majority of drivers preferred that the right lane of the highway be dedicated to ATPs. This percentage was greater for short ATPs compared to long ATPs. Part of the preference for long ATPs to use the left lane is likely due to their impact on the subject vehicle entering or exiting the highway. The complete survey response is shown in **Table 11**.

Table 11: Lane preferred by car drivers to be dedicated to ATPs

Preferred Lane	Short ATP (5 vehicles)	Long ATP (10 vehicles)	All ATPs
Left Lane	3 (25%)	5 (42%)	8 (33%)
Center Lane	1 (8%)	2 (17%)	3 (13%)
Right Lane	8 (67%)	5 (42%)	13 (54%)
Total	12 (100%)	12 (100%)	24 (100%)

5 Conclusions and Recommendations

Automated Truck Platooning (ATP) enables a group of commercial trucks to move safely together with higher speeds and shorter headways between them. The success of ATPs in the future strongly depends on how other drivers on the road interact with them. A review of the literature in the field of ATP showed that most studies have been more focused on the ATP and its drivers. There was little research on the driving behavior of vehicles surrounding the ATP. As a result, for this project, the NJIT research team investigated how other drivers interact with and react to their presence of ATPs on highways. The following objectives are accomplished in this project:

- Current research on driving behavior of ATP drivers and the driver of other vehicles surrounding the ATPs were reviewed and summarized.
- A high-fidelity simulation environment for conducting the tests was built using the NJIT driving simulator (DS).
- A connection was made between the DS and VISSIM traffic micro-simulation software. VISSIM was used to control the driving behavior of the ATPs.
- Four different categories of scenarios for three different ATP platoon lengths, or twelve tests in total, were designed and a questionnaire was also prepared for all driver participants.
- Tests were conducted through the participation of twelve licensed drivers
- The data obtained were analyzed and presented.

Some of the findings are briefly reviewed below:

- When vehicles approach an ATP, most drivers maintain or increase their speed in order to pass the ATP as soon as possible.
- When an ATP approaches the vehicles, around one-third of drivers tend to stay in their lane and increase their speed in order to compete with the ATP and avoid being passed.
- When an ATP changes lanes to exit the highway, about one-half of drivers brake, with or without a lane change, in order to keep a safe distance from the ATP.
- When a vehicle wants to take the exit on the right and the ATP is driving in the right lane, about one-half of the drivers brake to tailgate the ATP and then take the exit when the ATP has cleared. The other drivers increase their speed to either overtake or cut-in to the ATP.
- When a vehicle wants to merge to the mainline from the right and the ATP is driving in the right lane, more than sixty percent of drivers decrease their speed and merge after the ATP has cleared the entrance area. This percentage is higher for larger platoons.
- The drivers of the surrounding vehicles of the ATPs prefer the right lane of a three-lane roadway, rather the center or left lane, to be dedicated to ATPs.

In order to make the experiments more realistic and produce more useful results in the future, the following improvements are recommended for future research:

- The simulation environment should be made more complex through the additional of both horizontal and vertical curves.
- Other traffic in addition to the subject driver and the ATP should be added to the simulation. This additional traffic should include both autos and trucks.
- A broader range of scenarios should be investigated especially varying the level of congestion on the roadway.
- A larger number of subject drivers with a wider range of characteristics, especially age and years of driving experience, should be recruited to participate.

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Appendix A. Questionnaire

General & Health Information

Name:

Age:

Gender: Male   Female

Please complete the questionnaire by circling the answers where applicable

1. Do you have a valid driver's license?

   a) Yes   b) No

2. Have you been involved in any accident(s) within the past 3 years?

   a) Yes   b) No

3. If yes, please state the number of crash(s) involved in and the type.

4. Do you need to wear glasses or contact lenses while driving?

   a) Yes   b) No

5. Do you have any health problems that affect your driving?

   Yes   b) No   If yes, please state

6. Do you experience any inner ear, dizziness, vertigo, or balance problems while driving?

a) Yes   b) No

7. How often do you drive?

a) Daily   b) Once a week   c) Occasionally

8. For how long have you been driving?

a) Less than 1 yr   b) Between 1 – 5 yrs   c) Between 5 – 15 yrs   d) More than 15 yrs

Q1. What was your primary driving maneuver when you approached a truck platoon (Check all that apply)

Platoon Length	Platoon Location	Stay in lane	Change lane	Maintain speed	Accelerate	Brake
Short (5 Trucks)	On the same lane					
	On your right					
	On your left					
Long (10 Trucks)	On the same lane					
	On your right					
	On your left					

Q2. What was your primary driving maneuver when a platoon approached you (Check all that apply)

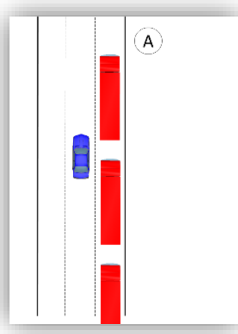
Platoon Length	Platoon Location	Stay in lane	Change lane	Maintain speed	Accelerate	Brake
Short (5 Trucks)	On the same lane					
	On your right					
	On your left					
Long (10 Trucks)	On the same lane					
	On your right					
	On your left					

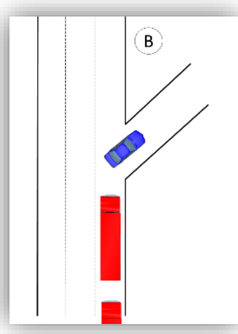
Q3. What was your primary driving maneuver if a platoon changes lane to take the exit ramp when you drove forward around the ramp area (Check all that apply).

Platoon Length	Stay in lane	Change lane	Maintain speed	Accelerate	Brake
Short (5 Trucks)					
Long (10 Trucks)					

Q4. What was your primary driving maneuver if a platoon existed on the right-most lane when you attempted to take the exit ramp.

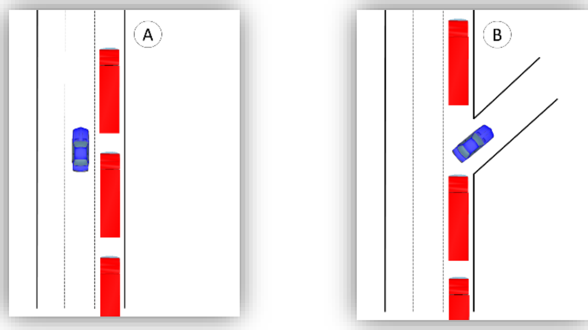
[1] Accelerate to pass the platoon: By accelerating, you overtook the platoon and drove through the ramp before the platoon reaches the ramp.





[2] Brake to tailgate the platoon: You reduced your speed to let the platoon pass you. Then you changed lane and followed the platoon. You drove through the exit ramp when you reached that.

[3] Cut-in to the platoon: While the platoon was passing the exit ramp, you drove between the trucks and took the exit ramp.

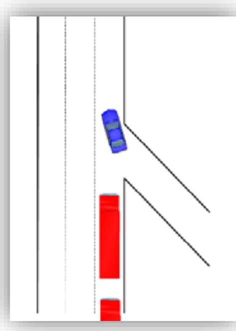


[4] Do nothing special:

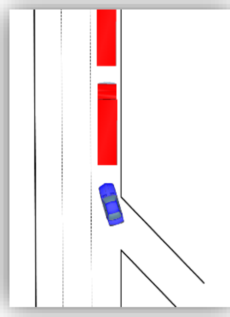
Platoon Length	[1]	[2]	[3]	[4]
Short (5 Trucks)				
Long (10 Trucks)				

Q5. What was your primary driving maneuver if a platoon existed on the right-most lane when you attempted to merge into the mainline.

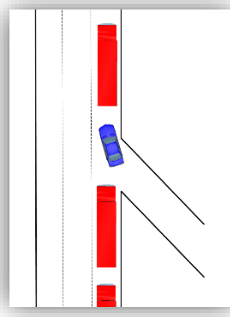
[1] Accelerate to pass the platoon: By accelerating, you reached the merging point ahead of the platoon and drove into the freeway.



[2] Brake to tailgate the platoon: By reducing your speed, you let the platoon pass the merging point and then you entered the freeway.



[3] Cut-in to the platoon: While the platoon was at the merging point, you drove between the trucks and entered the freeway.



[4] Do nothing special.

Platoon Length	[1]	[2]	[3]	[4]
Short (5 Trucks)				
Long (10 Trucks)				

Q6. If a lane is necessarily dedicated for automated truck platooning, which lane do you prefer?

Platoon Length	Left-most Lane	Middle-lane	Right-most lane
Short (5 Trucks)			
Long (10 Trucks)			

Appendix B. Acceleration Diagrams

During the tests, quantitative measures of the subject vehicle (e.g. acceleration, speed, location coordinates) are collected each 1/10 of a second for post-processing and analysis. The following diagrams are prepared based on the acceleration of individual subject vehicles during different tests.

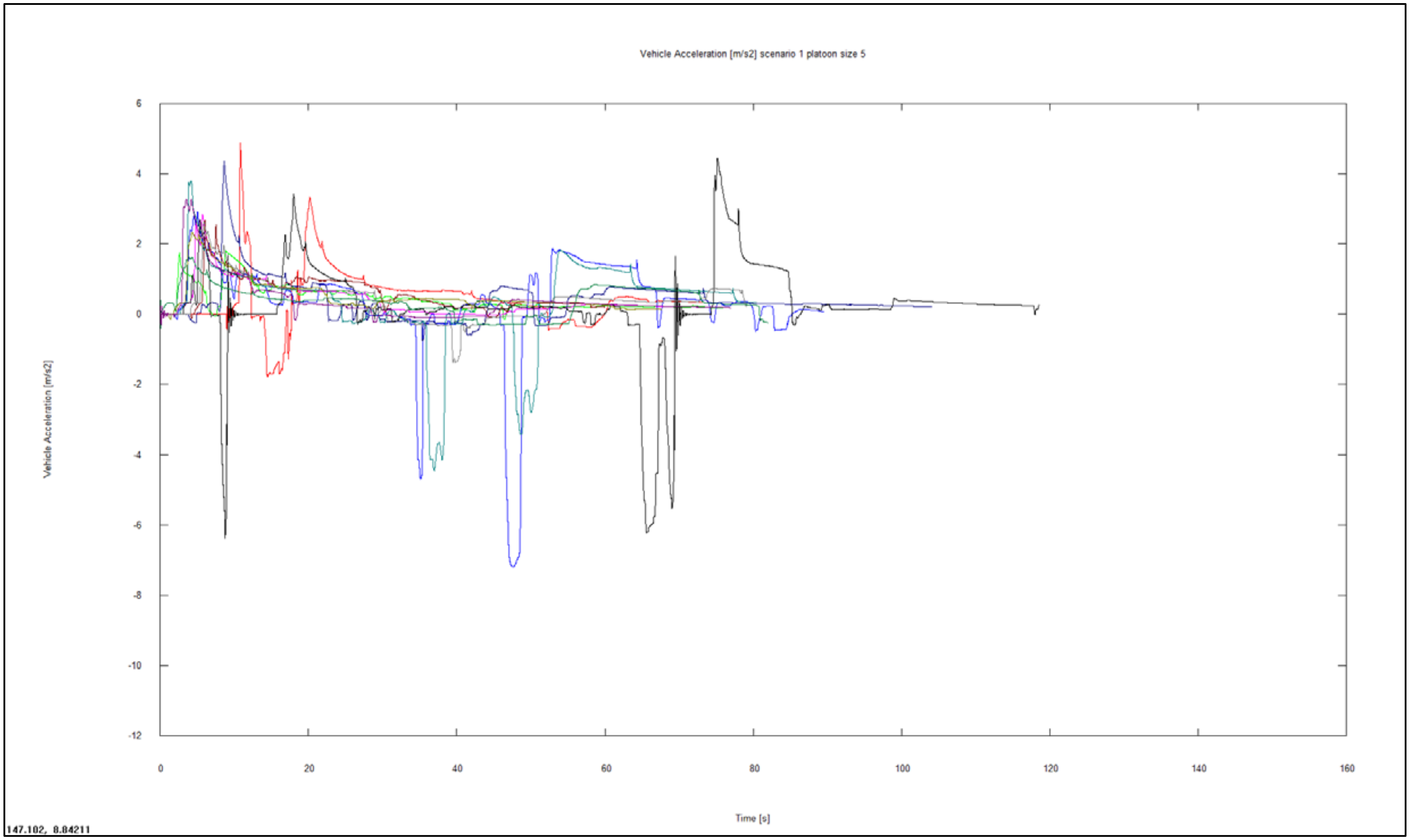


Figure 17 Subject vehicle acceleration over time in scenario 1 with platoon size 5

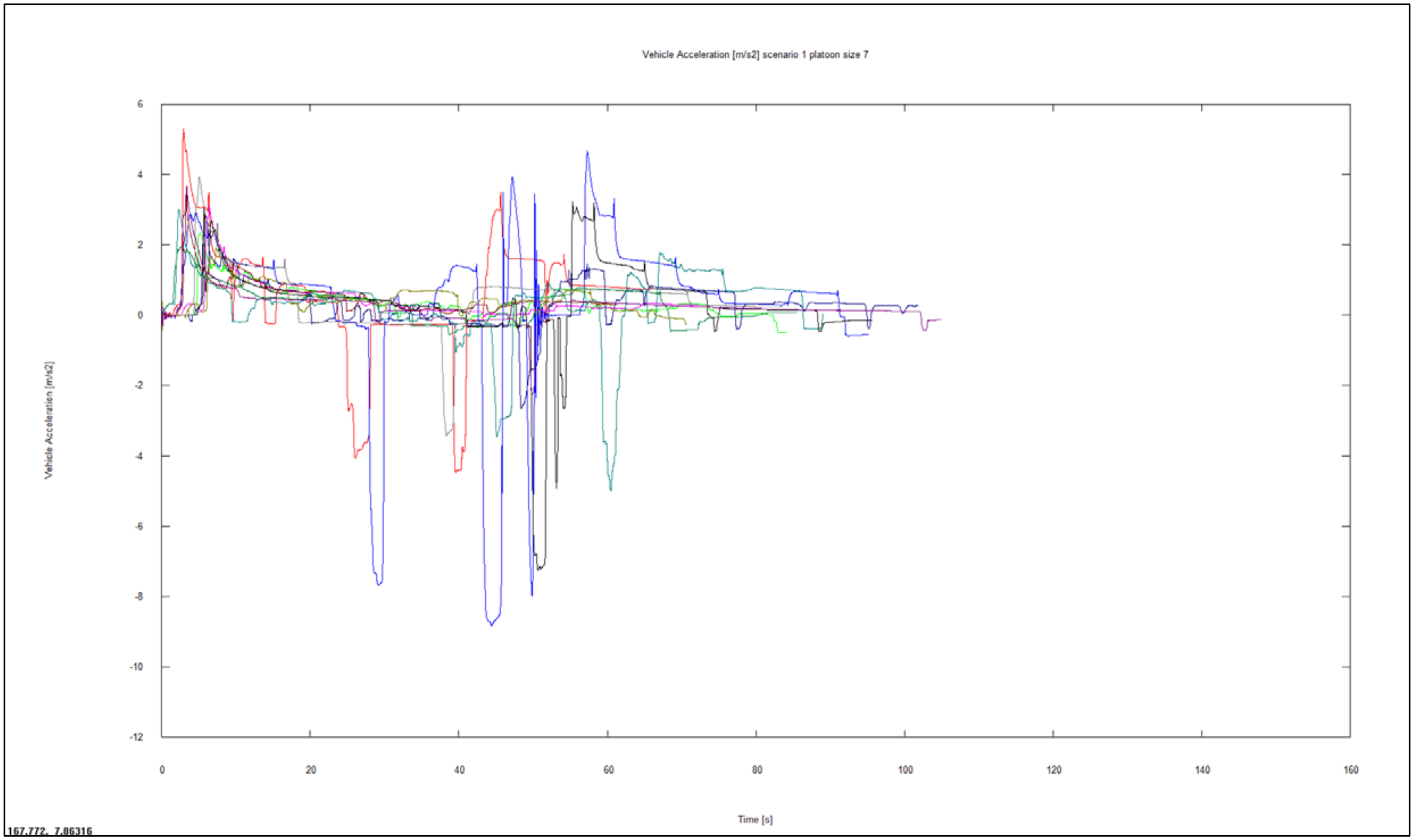


Figure 18 Subject vehicle acceleration over time in scenario 1 with platoon size 7

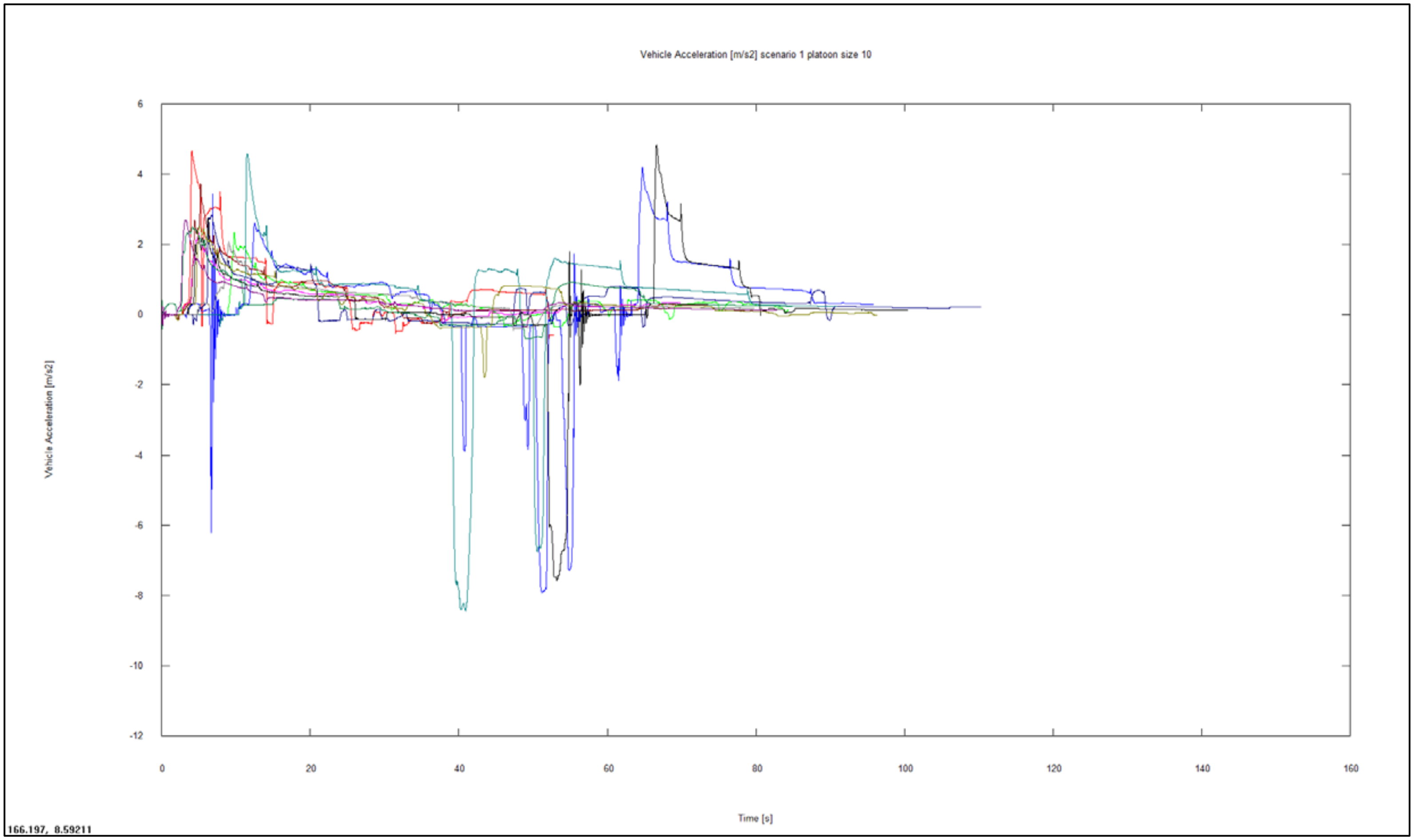


Figure 19 Subject vehicle acceleration over time in scenario 1 with platoon size 10

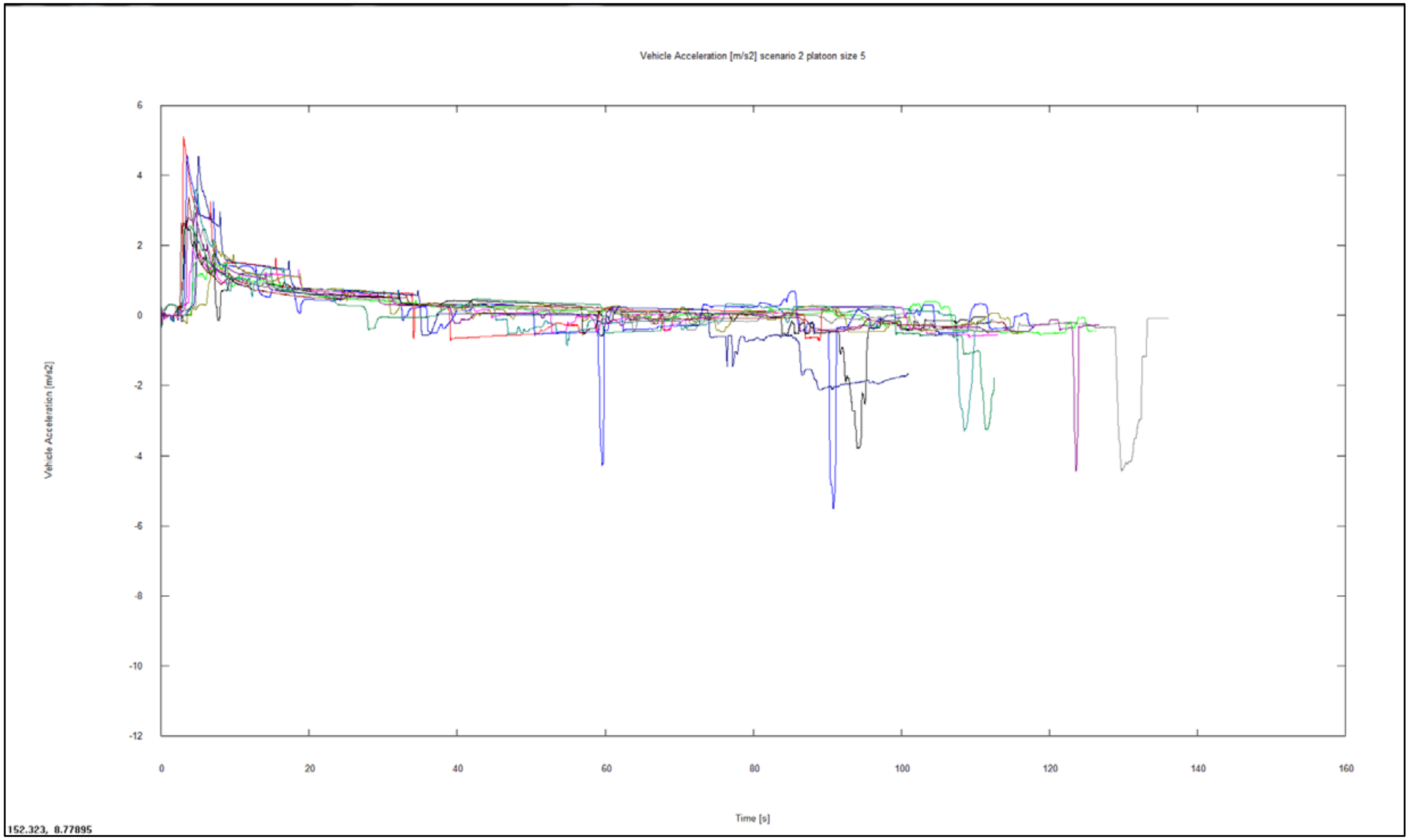


Figure 20 Subject vehicle acceleration over time in scenario 2 with platoon size 5

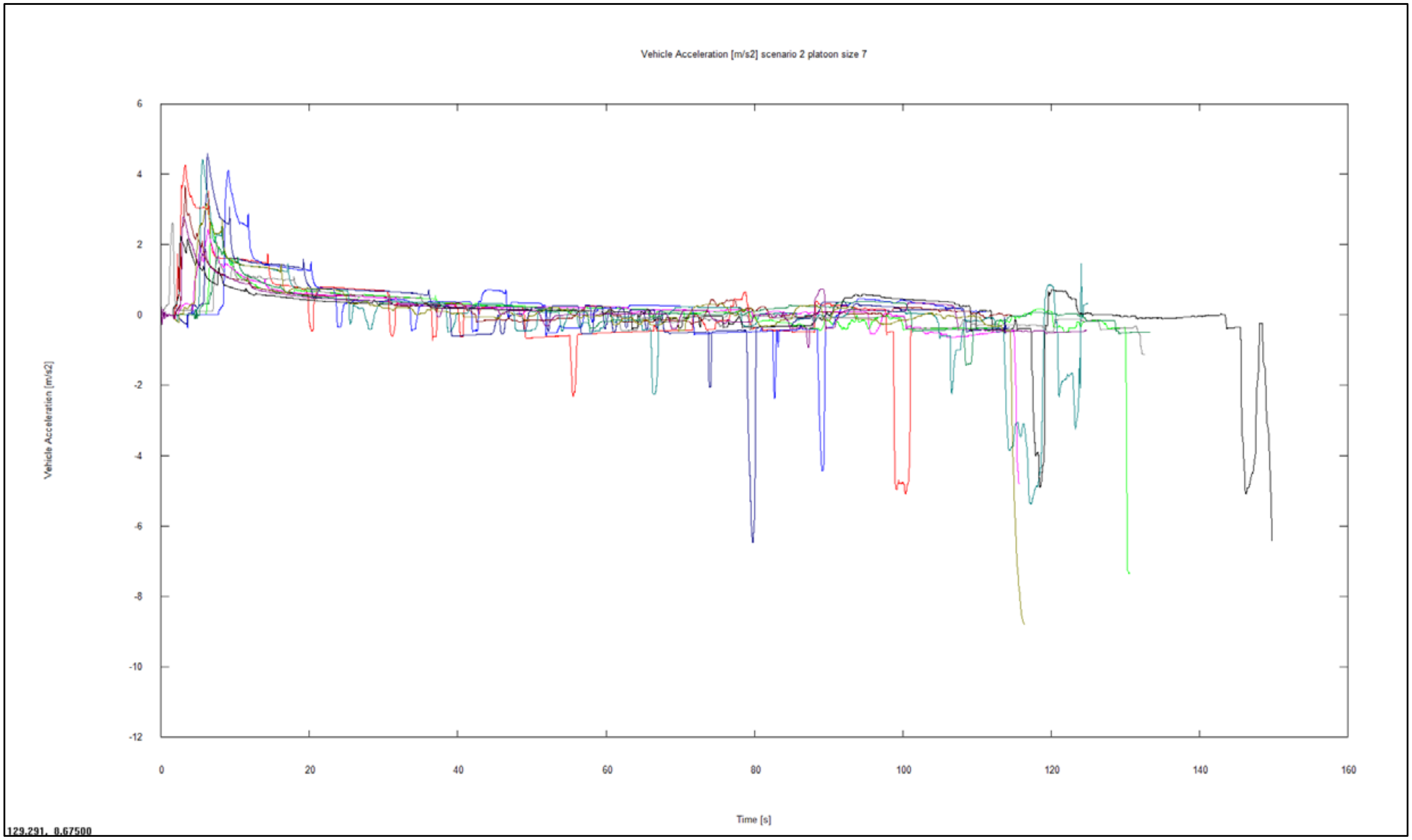


Figure 21 Subject vehicle acceleration over time in scenario 2 with platoon size 7

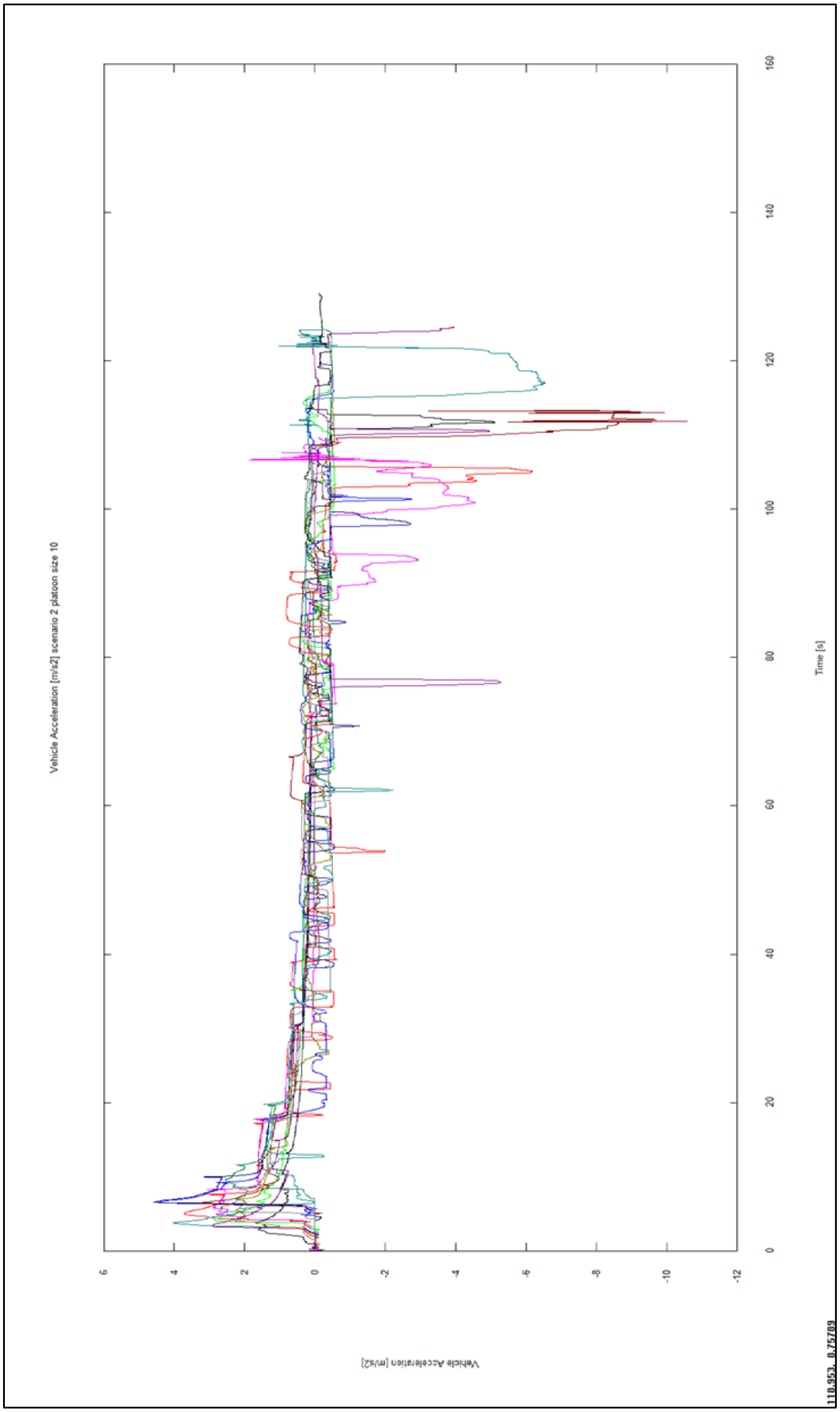


Figure 22 Subject vehicle acceleration over time in scenario 2 with platoon size 10

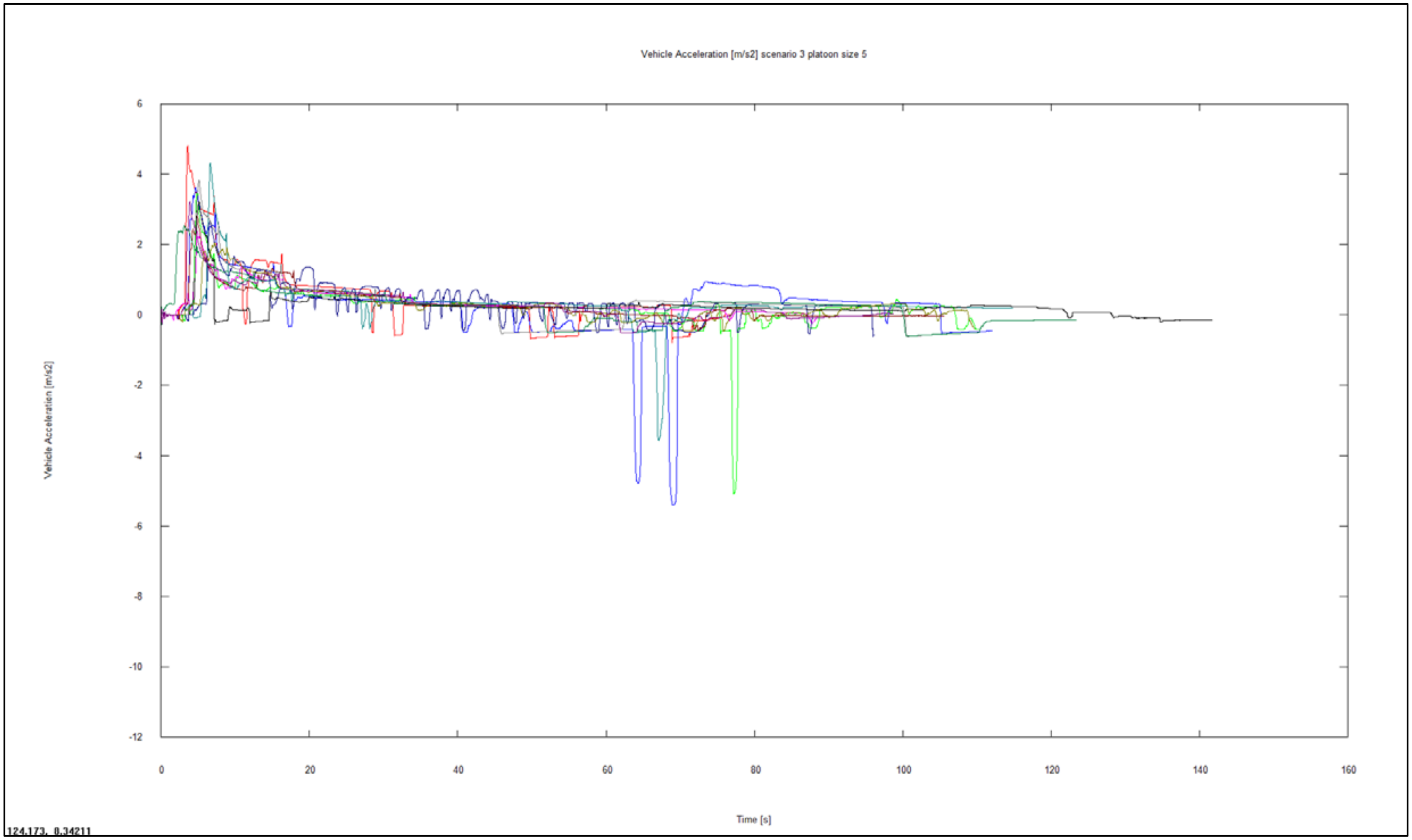


Figure 23 Subject vehicle acceleration over time in scenario 3 with platoon size 5

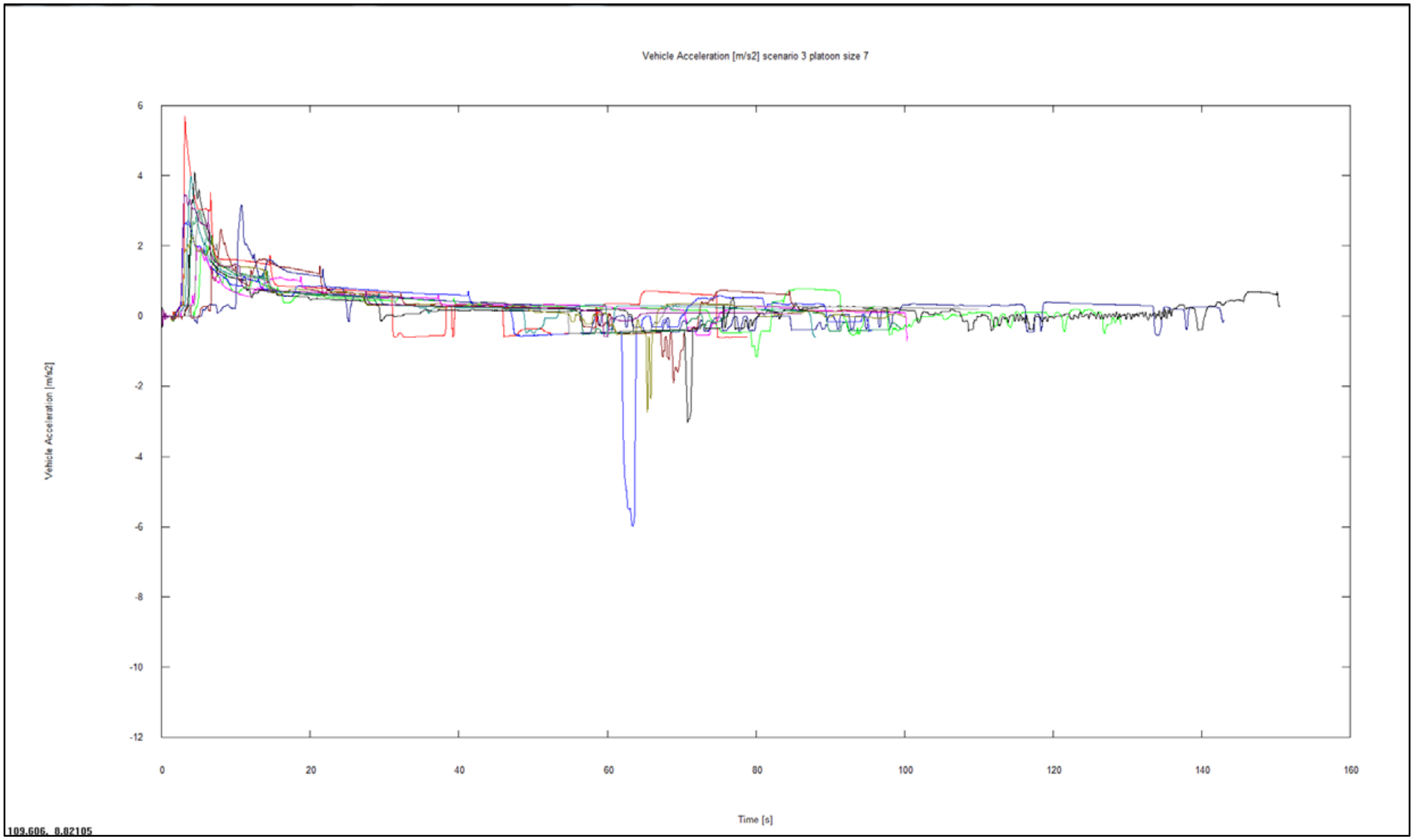


Figure 24 Subject vehicle acceleration over time in scenario 3 with platoon size 7

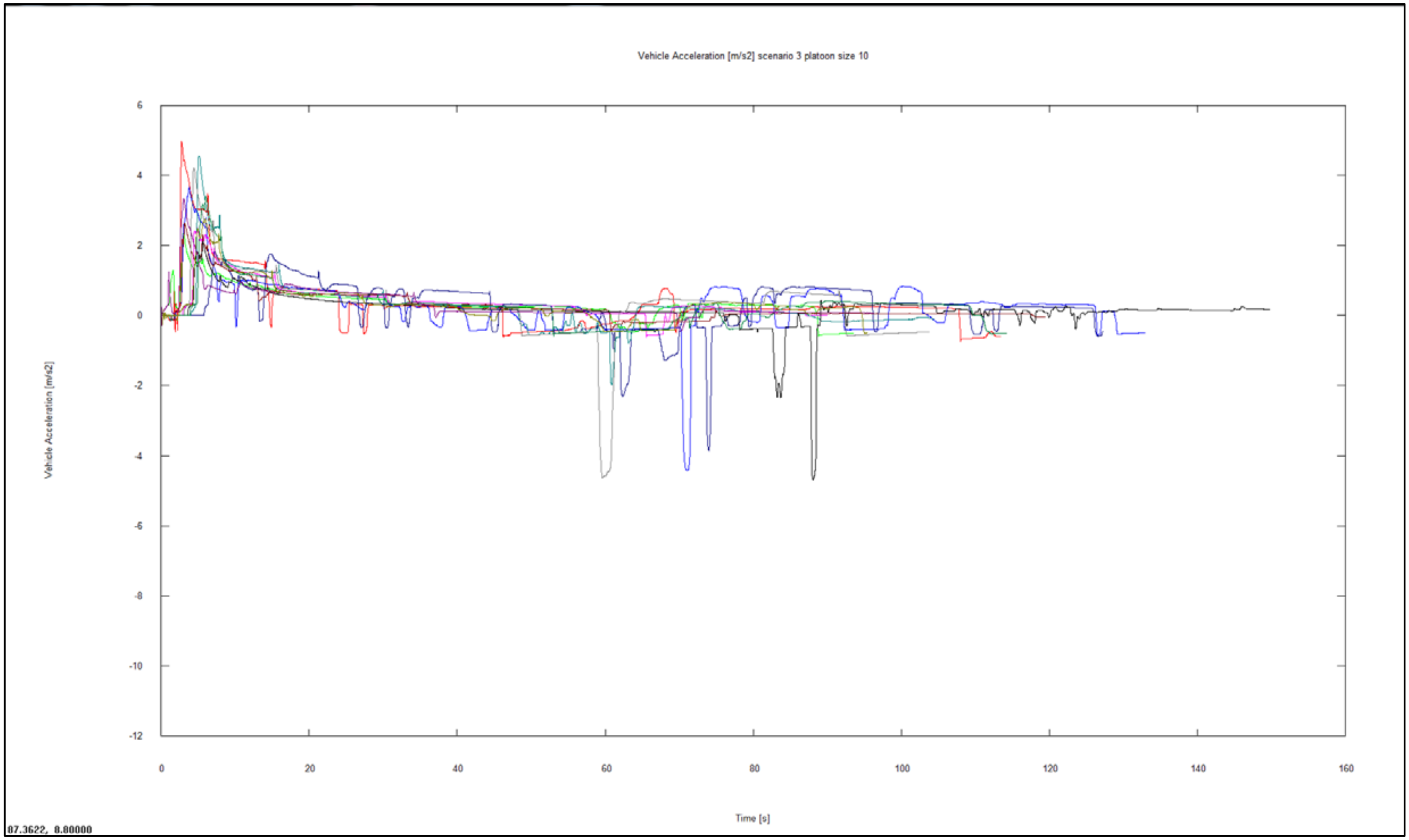


Figure 25 Subject vehicle acceleration over time in scenario 3 with platoon size 10

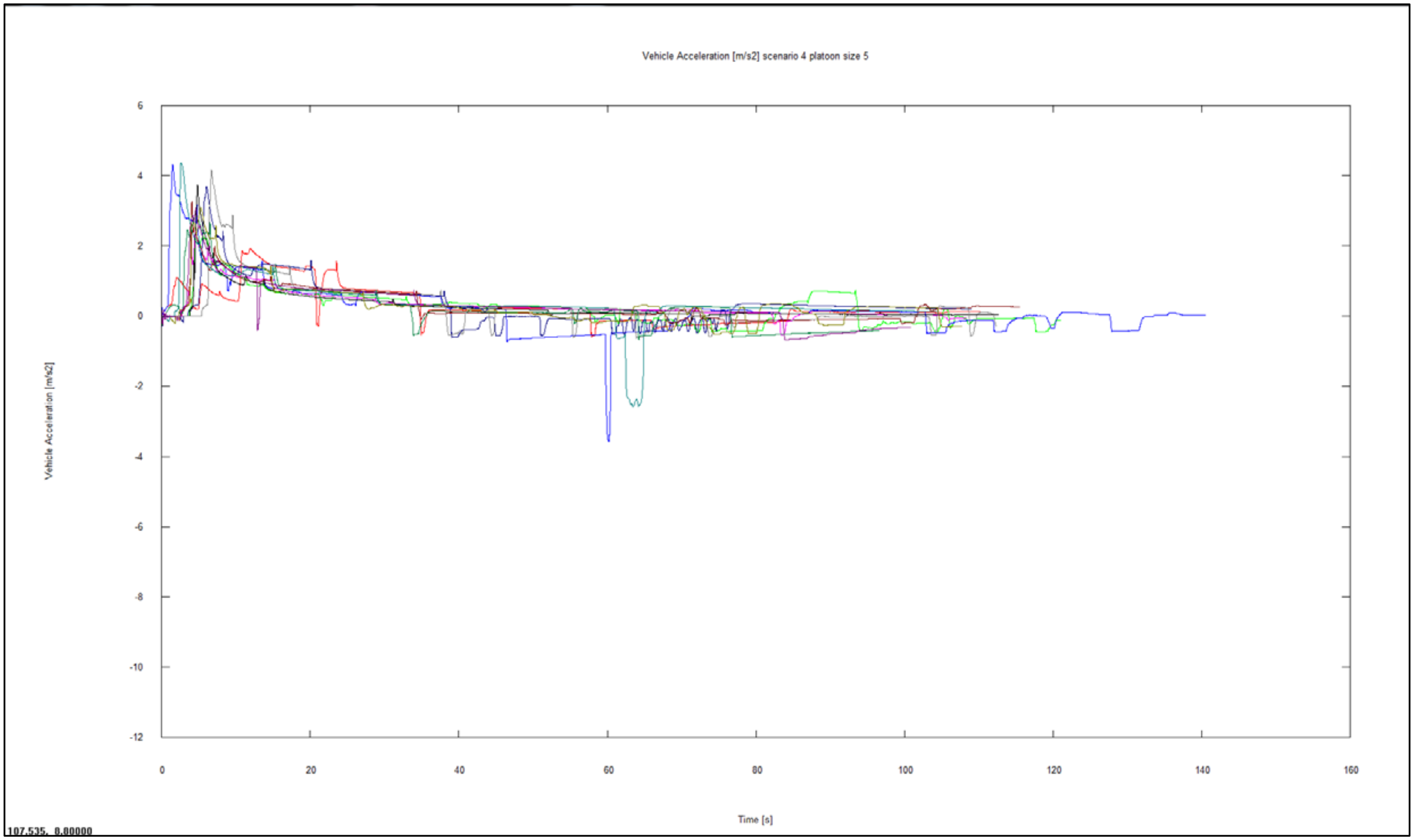


Figure 26 Subject vehicle acceleration over time in scenario 4 with platoon size 5

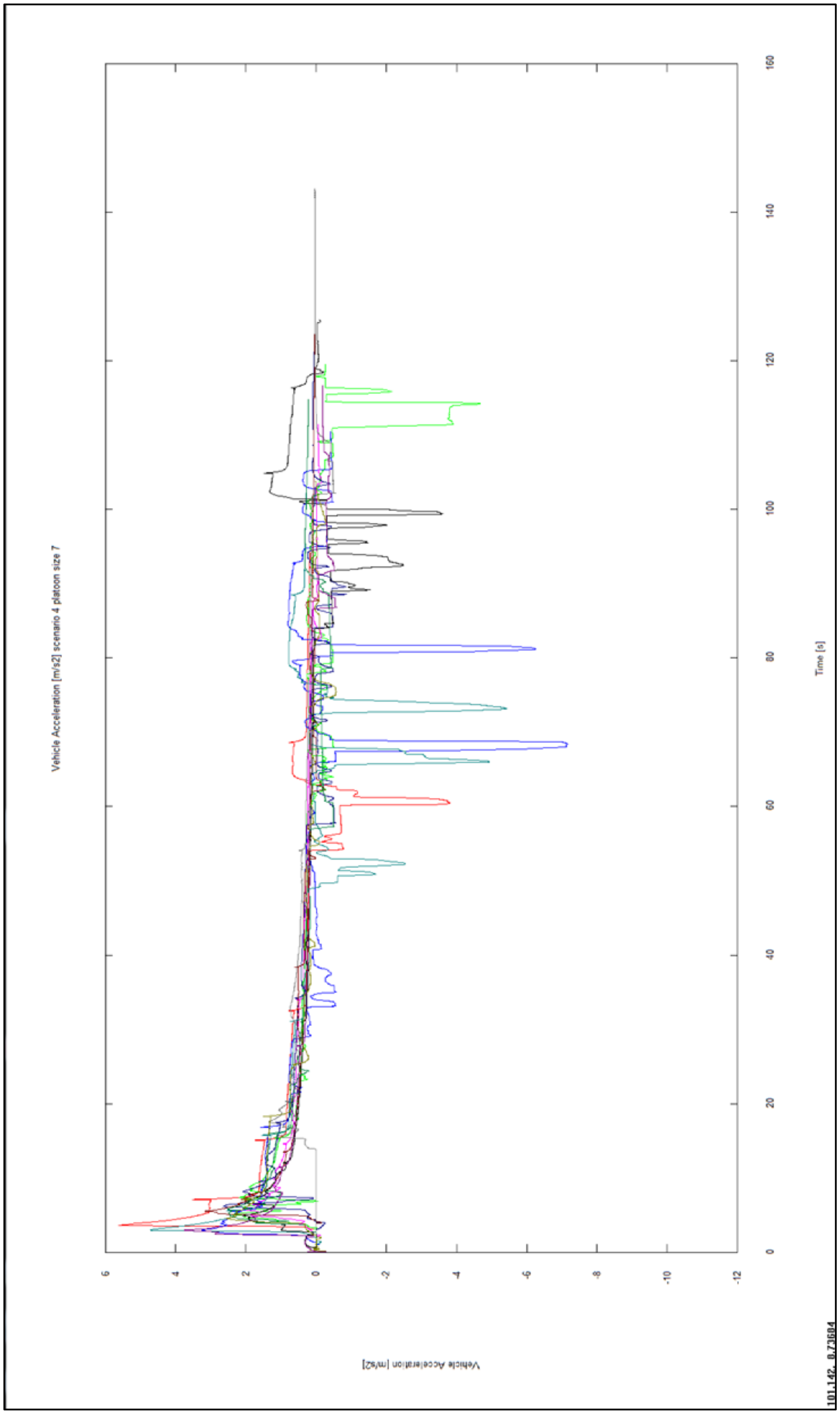


Figure 27 Subject vehicle acceleration over time in scenario 4 with platoon size 7

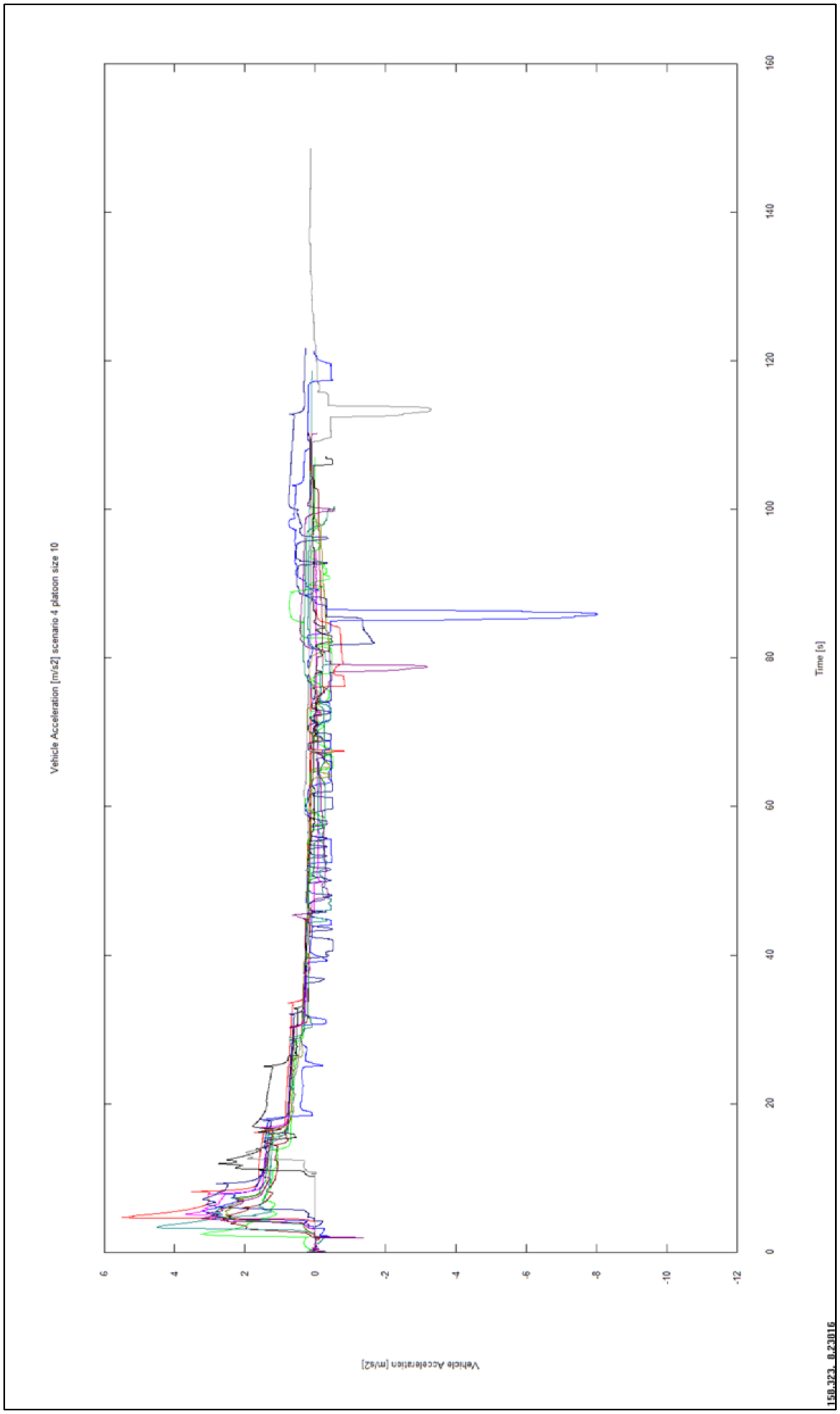


Figure 28 Subject vehicle acceleration over time in scenario 4 with platoon size 10