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Impacts of Autonomous Truck-Mounted Attenuator (ATMA) on INDOT Work Zone Safety, Mobility, and Worker Productivity

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16. Abstract

Work zone safety has been a major concern for many stakeholders, including the state Departments of Transportation (DOTs). To prevent DOT workers, especially truck mounted attenuator (TMA) drivers, from injuries, the Autonomous Truck Mounted Attenuator (ATMA) technology was developed. To understand the current testing and deployment status of ATMA, we interviewed project managers and researchers in four state DOTs who had experience with the ATMA system. We then systematically reviewed, tested, and evaluated the ATMA system in both simulation and real-world environments under various operating scenarios, traffic conditions, and mobile work zone operations. Indiana Department of Transportation (INDOT) workers' perception of using the ATMA system was also collected. Results suggested that the ATMA system can be successfully implemented in most of the selected INDOT road maintenance activities with good performance. INDOT workers were also comfortable to operate the ATMA system after training and welcomed this new technology. Longer exposure to the ATMA system was a key factor impacting workers' behavior and evaluation toward ATMA. While the ATMA system demonstrated significant benefits in saving transportation workers' lives and reducing their risk of injuries; however, one limitation was that the system's cost is relatively high at the current stage, based on a cost-benefit analysis.

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EXECUTIVE SUMMARY

Introduction

Due to a high number of work zone related accidents and worker fatalities and injuries, work zone safety is a significant concern for transportation agencies, including the drivers of Truck Mounted Attenuators (TMAs). A new technology, Autonomous Truck-Mounted Attenuator (ATMA), was developed that equips TMA trucks with autonomous driving capabilities. With ATMA, a driver is not needed in the TMA truck and therefore will not be injured in the event of a crash. Several state Department of Transportation (DOTS) have tested the ATMA system with a focus on painting operations. In this project, we interviewed the project managers and researchers at four state DOTs who have experience with the ATMA system. Then we further explored the implementation of the ATMA system in several Indiana DOT (INDOT) mobile work zone operations that require ground workers for (1) sweeping, (2) trash pickup, (3) crack sealing, (4) underdrain inspection, and (5) Raised Pavement Marker (RPM) inspection. We evaluated the functionality of the ATMA system on the five selected activities through both closed road tests and open road deployments on different types of roadways (interstate highways, trunk highways, local roads) and environmental conditions (day and night) during a 5-week period. INDOT workers' perception of the ATMA system's safety and productivity was collected after the open road deployment. To evaluate the ATMA system on mobility, a microscopic traffic simulation was performed based on real-world traffic data collected from the same locations as open road deployments. A cost-benefit analysis was conducted to determine the feasibility of the investment, and an overall evaluation and recommendations of the ATMA system are provided in this report.

Findings

The main findings of the study are summarized from the following five perspectives.

1. *Supported Mobile Work Zone Operations*

   - The ATMA was successfully implemented in four mobile work zone operations: sweeping, trash pickup, RPM inspection, and underdrain inspection.
   - The ATMA was implemented for various types of roads under test, including interstate highways, trunk highways, and local roads.
   - The ATMA system does not support the crack sealing operation because of the extremely low operating speed (e.g., 1 mph).

2. *ATMA Technology Evaluation*

   - The ATMA system performed well in test cases, including following commanded longitudinal gaps and speed, following commanded lateral gaps, performing turning maneuvers, reacting to obstacle intrusion, and performing automatic/emergency stops.
   - The ATMA system was successfully operated in varying traffic conditions and roadway environments with a "normal operation" status 96.62% of the time.
   - The main technical issue was that the autonomous driving function may occasionally disengage under GPS constrained scenarios (e.g., under an overpass).

3. *Workers' Perception*

   - Workers are comfortable operating the ATMA system after training.
   - Workers believe this new technology can improve their safety and productivity.
   - Longer exposure to the ATMA system impacts workers' behavior and evaluation toward ATMA. More experience with the ATMA system results in higher trust.
   - Age does not significantly impact workers' evaluation of the ATMA system.

4. *Impact on Mobility*

   - Higher traffic volume and slower ATMA operation speed result in greater impacts on traffic delays in all roadway types.
   - The time of day to implement the ATMA system should be carefully selected.

5. *Cost-Benefit Analysis*

   - The cost of procurement and maintenance of the ATMA system is still high because the technology is new and the market size is small.
   - The benefit-cost ratio is smaller than 1.0, given the current technology price and TMA-related crash statistics from Indiana.

Implementation

Based on the findings described above, the following ATMA implementation recommendations are provided.

- The ATMA system can be implemented in mobile work zone operations with specific moving speeds, such as sweeping, trash pickup, RPM inspection, and underdrain inspection.
- Special caution should be given when implementing the ATMA system under frequent GPS-denied or GPS-downgraded situations (e.g., urban canopy).
- Training should be provided to the leader truck driver on the operation and/or monitoring of the ATMA system. The impact of the ATMA truck on traffic should be considered when making maneuvers like lane changes, stops, and turns.
- The time of day and location to deploy the ATMA system should be carefully selected to avoid impacting traffic.
- Although the benefit-cost ratio is smaller than 1.0 at the current stage, with an increased technology maturity level and market size, the cost of the system will decrease in the future.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Motivation and Background

Road maintenance activities are crucial to ensure high quality of roadways (Weng et al., 2014). Workers during road maintenance activities are in high danger. From 2003 to 2019, 2,103 workers were killed in road construction zones in the U.S. (NIOSH, 2022). In Indiana, 14 deaths and more than 650 injuries occurred in INDOT work zones in 2018 (INDOT, n.d.). Additionally, studies have shown that mobile and slow-moving operations like stripping, painting, and crack sealing create significant speed differences between maintenance vehicles and normal traffic. These speed disparities are a key factor contributing to rear-end crashes in work zones (Tang et al., 2021; Weng et al., 2015) and the major type of crashes in Indiana (Tian et al., 2024). To protect workers in mobile work zone operations, traffic control devices such as Truck-Mounted Attenuator (TMA) are widely adopted. However, studies show that drivers of TMA trucks are at higher risk than other workers due to the high crash rate between the TMA and other traffic (Sun et al., 2020).

The Autonomous Truck-Mounted Attenuator (ATMA) system is developed to remove the driver from the TMA truck and improve their safety, by implementing autonomous driving technologies. Different from a typical autonomous driving vehicle, the ATMA system consists of two vehicles (or two trucks), which are a leader truck and a follower truck (i.e., the TMA). Both trucks are equipped with vehicle-to-vehicle (V2V) communication devices that enable real-time information transmission. The leader truck is operated by a human driver and its precise trajectory is sent to the follower truck in real-time. The follower truck is equipped with a by-wire-control system and can be operated autonomously. It receives the trajectory from the leader truck and tries to follow the trajectory with a predefined gap. The gap between the two trucks can be adjusted by the human operator in the leader truck to fulfill different operating conditions and speeds. A more detailed description of the ATMA system will be provided in the next section.

Several state DOTs have explored the ATMA system manufactured by Kratos with specific considerations. For example, the Colorado Department of Transportation (CDOT) initiated its ATMA study in 2017, making it the first state in the U.S. to implement this emerging technology. CDOT is mainly using the ATMA system for lane stripping on rural highways (Miller et al., 2021). Florida DOT (FDOT) conducted both closed-loop tests and open road tests on the ATMA system. Most of the test cases were successful, but a few did not meet expectations because the ATMA system drifted off the intended path, could not move to the shoulder quickly, or was unable to negotiate in roundabout scenarios (Agarwal et al., 2021). Tennessee DOT (TDOT) conducted 24 cases of ATMA test scenarios in their pilot study and concluded that the ATMA system is better for operations that require continuous movement. They also identified several issues of the ATMA and needs for refinement. For example, the ATMA should not be used for stop-and-go applications such as pothole patching (Kohls, 2021). Similarly, thirty-one ATMA system tests were performed by Missouri DOT (MoDOT) to evaluate the technology from different perspectives including communication loss, following distance and accuracy, obstacle detection, and emergency situations. The analysis quantitatively summarized the performance and showed expected performance (Tang et al., 2021). In addition to Kratos, Virginia Tech Transportation Institute (VTTI) was developing its own ATMA system in collaboration with industry partners (White et al., 2021).

Other state DOTs' ATMA implementations mainly focus on mobile work zone operations without human workers working between the leader and follower trucks, such as painting (Tian et al., 2022). However, a large portion of operations require workers working on the ground, such as crack sealing and RPM inspection. This project aims to investigate whether/how the ATMA system can be deployed for more mobile work zone operations other than painting. Furthermore, INDOT workers' perception and acceptance of this new technology is also collected.

1.2 ATMA System Introduction

The ATMA system in this project includes two trucks. The leader truck is provided by INDOT and retrofitted by Kratos and the follower truck (i.e., the ATMA) is provided by Kratos.

1.2.1 Overview of the Leader Truck

The leader truck is a 2021 Freightliner 108DD truck as shown in Figure 1.1. A rack holding two GPS antennas, a vehicle-to-vehicle (V2V) communication device, and a rear-facing camera are installed. A leader kit is installed in the vehicle cabin as shown in Figure 1.2.

Figure 1.1 Leader truck provided by INDOT and retrofitted by Kratos.

Figure 1.2 Leader kit inside the leader truck.

Figure 1.3 UI in the leader truck.

The leader kit includes a custom operator control unit (OCU) and independent emergency-stop (E-stop) controls. The OCU includes one automatic-stop (A-stop) button and several lights to indicate the system control unit (SCU) status, GPS signal connection, and operation modes. The independent E-stop controls have one E-stop button, and a light to indicate if an E-stop is initiated. A user interface (UI) is installed as shown in Figure 1.3. The human operator in the leader truck can control and monitor the status of the ATMA truck. The UI provides information such as warning messages, the current gap between the leader and follower truck, the current lateral offset between the leader and follower truck, the GPS connection status, and two camera views of the ATMA system. Also, the operator can control the commanded gap and commanded lateral offset by using the UI.

1.2.2 Overview of the Follower Truck

Figure 1.4 shows the follower truck. The follower truck is equipped with a V2V communication device to receive trajectory waypoints (i.e., GPS locations) from the leader truck. The leader truck sends its GPS location in 10 Hz to the follower truck, which is automatically controlled to follow the exact trajectory of the leader vehicle with a predefined gap and lateral offset. The steering of the follower vehicle is controlled by an actuator ring as shown in Figure 1.5. The acceleration and deceleration of the ATMA are controlled by a customized by-wire-control system as shown in Figure 1.6.

Figure 1.4 Follower truck provided by Kratos.

Figure 1.5 Actuator ring (the black ring under the steering).

In addition, several safety-related sensors are installed on the follower truck as shown in Figure 1.7. The front radar and LIDAR can detect objects in a lane up to 150 feet. An automatic stop will be initiated if the object is within 100 feet distance. The two LIDAR sensors on each side of the truck detect if an object appears on the side. The inside and outside of the follower truck are both equipped with E-stop buttons as shown in Figure 1.8 and Figure 1.9, respectively. The workers inside and outside of the follower truck can initiate an E-stop by pushing either button.

1.2.3 ATMA System Operation

Three workers are needed to operate the ATMA system. Two workers are required in the leader truck

Figure 1.6 Follower truck customized by-wire-control system that controls the brake and gas pedals.

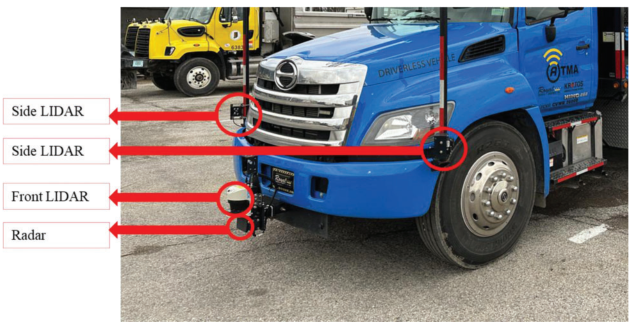

Figure 1.7 Rader and LIDAR sensor on the follower truck.

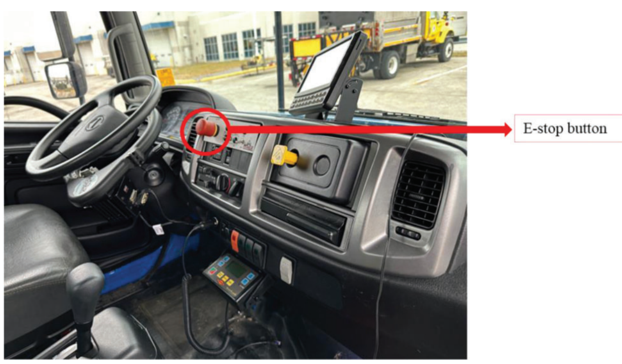

Figure 1.8 The E-stop button inside the follower truck.

with one worker driving and one worker monitoring and operating the ATMA via the UI. One worker is required in the follower truck's driver site to take over the control under emergency situations. Note that the safety operator in the follower truck is required by existing Indiana autonomous driving related regulations. In the future, if an exemption is approved or the regulations are changed, the safety operator can be removed from the follower truck. Figure 1.10 show the ATMA system during operation.

Figure 1.9 The E-stop button outside the follower truck.

Figure 1.10 ATMA system during operations.

2. STATE-OF-PRACTICE DEPLOYMENT OF ATMA

To better understand the current testing and deployment status in other states, an interview was performed with project managers and researchers who have experience with the ATMA system. The objectives of the interview are to collect (1) the current implementations status of ATMA, and (2) the strengths and weaknesses of the ATMA system. The interview study consists of three steps, which are the development of semi-structured interviews, data collection, and data analysis.

TABLE 2.1
Basic information of interviewees

State DOT	Region of U.S.	Number of Interviewees	Role of the Interviewees
Virginia DOT (VDOT) and Virginia Tech Transportation Institute (VTTI)	East	2	One project manager and one researcher
Colorado DOT (CDOT)	West	2	Two project managers
Minnesota DOT (MnDOT)	Midwest	1	One project manager
Missouri DOT (MoDOT)	Midwest	1	One researcher

The semi-structured interview was designed to gather information on the current implementation of ATMA systems in state DOTs, as well as workers' perceptions, trust, actions, and productivity related to ATMA. Additional comments from the interviewees were collected at the end of the interview. The study was approved by Purdue's Institutional Review Board (IRB). A total number of six states from different regions in the U.S. were contacted by email and six people from four states responded to our interview request. The information of six interviews from the four states is shown in Table 2.1. Four of them were state DOT project managers and two of them were researchers who also participated in the ATMA study in their corresponding states. The interviewed state representatives are from different regions with different terrains and climates and thus can provide a comprehensive picture of ATMA implementation in the U.S.

The findings are summarized below. More details can be referred to Tian et al., 2022.

Improving safety is the main benefit of the implementation of ATMA. All state DOT project managers mentioned safety is the primary motivation for them to adopt the ATMA system. Statements such as "Safety is the top priority," "It is really a safety benefit more than anything," "I think the most significant benefit is definitely safety," and "Leadership really likes it because of that potential safety benefit in the work zone" were used by the interviewees to highlight the safety benefits. Some state DOTs indicated that although the initial investment in the ATMA system is high, the investment in ATMA will be recouped by preventing crashes and injuries among state DOT workers. Consequently, the ATMA system offers long-term cost-saving benefits.

The challenges of implementation of ATMA are summarized from three perspectives, including technology, human behavior, and regulation. The technological perspective summarizes the challenges resulting from the limitations of the current ATMA system. The human behavior perspective encompasses the challenges arising from workers. The regulation perspective is about autonomous driving related regulations that may impact the ATMA deployment.

- The main challenge from the technological perspective is the unstable connection to the GPS signal since all DOTs mentioned they encountered GPS connection issues. Another technical issue is related to the control logic. For example, the speed control of the follower truck should be updated to make closing gaps between the leader truck and the follower truck faster and smoother.
- The challenges from the human behavior perspective include that continuous training should be provided to workers if they have not operated this technology for a long time (e.g., 1 year).
- As for the regulation perspective, since some states do not allow autonomous operations of vehicles on public roads, one worker must be present in the follower truck as a safety operator, which diminishes the primary motivation for deploying the ATMA.

3. ATMA SYSTEM FIELD EVALUATION

The ATMA system was tested in Indiana through both closed road tests and open road deployments.

3.1 Closed Road Test Plan and Result Summary

The following 25 closed road test cases are designed to test ATMA's performance from seven aspects, which are safety, following accuracy, lateral accuracy, turning capacity, obstacle detection, operational test, and loss of communication. Table 3.1 summarizes the closed road test results. The detailed information for each case can be found in Appendix B.

3.1.1 Limitations and Problems

Overall, the ATMA system passes all closed road testing. The only limitation is that the ATMA system failed the slalom test when the operating speed is 10 mph and 15 mph. The follower truck fails to follow the leader truck's trajectory with the commanded gap. Note that this is an extreme testing case which does not usually happen in real world operations.

3.2 Open Road Test Results

3.2.1 Open Road Test Plan

The open road test covers five mobile work zone operations, including sweeping, trash pickup, crack sealing, RPM inspection, and underdrain inspections. These operations are tested on various road types, including interstate, trunk highway, and state highway. The detailed test plan is illustrated in Table 3.2.

TABLE 3.1
ATMA system closed road test and results

	Test Case	Passed or Not	Description
		Focus Area 1: Safety	
1	Functionality Inspection	Yes	The whole system passes the functionality inspection, such as the UI, and sensors are installed properly and the turn signals on the lead and follow trucks are coordinated.
2	Automatic Stop-Leader Vehicle Internal Button (OCU)	Yes	Pushing the A-stop button stops the ATMA system without shutting down the engine.
3	E-stop: ATMA Internal Button	Yes	Pushing either E-stop button stops the ATMA system and shuts down the engine.
4	Emergency Stop: ATMA External Button	Yes	
5	Emergency Stop: Leader Independent E-Stop Button (Initiator)	Yes	
		Focus Area 2: Following Accuracy	
6	Following Distance Set by User Interface (UI) Panel	Yes	The following distance can be set by using the UI in the lead truck.
7	Following Accuracy on Straight Line	Yes	The follower truck can follow the trajectory of the leader truck with high accuracy under all 5 mph, 10 mph, and 15 mph straight-line operations.
8	Following Accuracy on Slalom Course	Partially passed	The follower truck can follow the trajectory of the leader truck with high accuracy under a 5-mph slalom course operation. However, the follower truck is stopped for 10 mph and 15 mph slalom course operations.
		Focus Area 3: Lateral Accuracy	
9	Lane: Changing Accuracy	Yes	The ATMA system can be operated with high accuracy when performing the lane change.
10	Lateral Offset	Yes	The follower truck can be set to have a lateral offset to the leader truck.
		Focus Area 4: Turning Capacity	
11	Minimum Turning Radius	Yes	The minimum turning radius for the ATMA is 25 feet for a left turn and 35 feet for a right turn.
12	Curve	Yes	The follower truck can follow the leader truck's trajectory with high accuracy when passing a curve section.
13	Roundabouts	Yes	The ATMA system can navigate a roundabout with a 65-foot radius.
		Focus Area 5: Obstacle Detection	
14	Obstacle Detection: Front	Yes	The ATMA system can detect obstacles in front of the vehicle and initiate a stop.
15	Obstacle Detection: Side	Yes	The ATMA system can detect the obstacles on the side and not stop.
16	Vehicle Intrusion	Yes	The ATMA system can detect the intruding vehicle and initiate a stop.
17	Bump Obstacle Test	Yes	The ATMA system can pass small obstacles such as speed bumps without interfering with normal operation.
		Focus Area 6: Operational Test	
18	Speed to Catching Up with the Gap	Yes	The follower truck can increase its speed to catch the newly commanded short gap.
19	Braking: Leader Vehicle	Yes	The follower truck can initiate an A-stop when the leader truck brakes to stop.

(Continued)

TABLE 3.1
(Continued)

	Test Case	Passed or Not	Description
20	Leader Reverse	Yes	The follower truck can initiate an A-stop when the leader truck reverses.
21	Acceleration: Deceleration	Yes	The follower truck can accelerate and decelerate to follow the speed change of the leader truck.
	Focus Area 7: Loss of Communication		
22	Downgraded GPS Signal: 60 Seconds	Yes	The ATMA system can still be operated automatically with a loss of GPS signal for 60 seconds. The ATMA can initial A-stop when the GPS signal is lost and not recovered.
23	Downgraded GPS Signal: Forever	Yes	
24	Loss of Communication (Single V2V Radio)	Yes	The ATMA system can still be operated automatically with the loss of a signal V2V communication, and initiate A-stop when both V2V communication is lost.
25	Loss of Communication (Both V2V Radios)	Yes	

TABLE 3.2
Summary of ATMA open road test schedule

No.	Date	Activity	Road	Lighting Condition
		Rental Period 1		
1	12.12.2022	Trash pickup	US-31	Day
2	12.13.2022	Trash pickup	SR 19	Day
3	12.14.2022	Sweeping and trash pickup	I-465	Day
		Rental Period 2		
1	07.17.2023	Sweeping and trash pickup	I-465	Night
2	07.18.2023	ATMA was transferred from Indy to Tipton unit		
3	07.19.2023	Underdrain inspection	US-31	Day
4	07.20.2023	Underdrain inspection	I-69	Day
5	07.24.2023	RPM inspection	I-69	Day
6	07.25.2023	Crack sealing (crack sealing machine was not working)	I-69	Day
7	07.26.2023	RPM inspection	US-31	Day
8	07.27.2023	The day was off because of INDOT family day		
9	07.31.2023	ATMA demonstration	West Lafayette	Day
10	08.01.2023	The two days were off because the whole Tipton unit worked on the pipe project		
11	08.02.2023			
12	08.03.2023	Crack sealing	US-31	Day
13	08.07.2023	The day was off because of the rain		
14	08.08.2023	Crack sealing and RPM inspection	US-31	Day
15	08.09.2023	Crack sealing	US-31	Day
16	08.10.2023	Underdrain inspection	US-31	Day

3.2.2 Open Road Test Results

Tables 3.3, 3.4, and 3.5 summarize the ATMA system status under different operations. Overall, the ATMA system can be operated normally (IDLE+ ROLLOUT+RUN+ASTOP+RUN_PAUSED) on an average of 96.62% (std: 3.34%) of the whole deployment time period. However, some ASTOP_ECRUMB_ ERROR and ERROR statuses occurred in most of the test days. The total number of errors each day is listed in Figure 3.1. When these errors occurred, the ATMA system usually needed to be restarted or reconfigured.

3.2.3 Limitations and Problems

Based on the open-road-test results, the following limitations and problems are found.

First, the crack sealing operation was found unsuccessful with the existing ATMA system. The reason is that the current ATMA system is designed to be operated faster than 4 mph. The follower truck is not able to follow the leader truck when its speed is slower than 4 mph. The follower truck remains on "stop" even though the actual gap is larger than the commanded gap as shown in Figure 3.2. In the crack sealing operation, the workers need to walk at a speed around

TABLE 3.3
Open road test results: sweeping and trash pickup

	12.12.2022 US-31		12.13.2022 SR 19		12.14.2022 I-465		07.17.2023 I-465	
	Percentage	Seconds	Percentage	Seconds	Percentage	Seconds	Percentage	Seconds
ASTOP	0.049	8.55	1.46	220.42	3.70	237.09	NA	NA
ASTOP_ECRUMB_ERROR	1.17	205.03	0.84	127.73	5.64	361.53	4.74	350.25
IDLE	24.26	4,224.13	30.54	4,601.15	24.57	1,573.18	29.06	2,144.75
ROLLOUT	1.38	240.28	5.54	835.91	4.75	304.13	8.98	663.01
RUN	72.98	12,705.36	61.44	9,255.96	60.49	3,871.94	53.27	3,930.66
ERROR	NA	NA	0.15	22.82	0.83	53.11	3.92	289.31
Total Successful Operation Time (seconds)	17,169.77		14,913.44		5,886.34		6,738.42	
Total Successful Operation Percentage	98.67		98.98		93.51		91.31	

TABLE 3.4
Open road test results: RPM inspection

	07.24.2023: I-69		07.26.2023: US-31		08.08.2023: US-31	
	Percentage	Seconds	Percentage	Seconds	Percentage	Seconds
ASTOP	NA	NA	0.07	13.05	NA	NA
ASTOP_ECRUMB_ERROR	2.21	149.69	1.76	320.66	0.88	57.72
IDLE	33.58	2,267.47	14.91	2,702.95	6.04	395.07
ROLLOUT	1.47	99.75	1.98	359.35	1.42	93.21
RUN	62.717	4,234.08	80.41	14,578.01	91.49	5,978.09
RUN_PAUSED	NA	NA	0.71	128.80	0.15	9.91
ERROR	NA	NA	0.13	25.16	NA	NA
Total Successful Operation Time (seconds)	6,601.3		17,769.11		6,476.28	
Total Successful Operation Percentage	97.76		98.01		99.1	

TABLE 3.5
Open road test results: underdrain inspection

	07.19.2023: US-31		07.20.2023: I-69		08.10.2023: US-31	
	Percentage	Seconds	Percentage	Seconds	Percentage	Seconds
ASTOP_ECRUMB_ERROR	0.06	11.18	8.93	1,659.54	1.04	81.60
IDLE	5.14	931.48	8.10	1,506.74	3.34	260.45
ROLLOUT	1.83	331.21	2.85	529.55	8.95	696.80
RUN	92.96	16,821.13	79.24	14,723.58	84.09	6,542.61
RUN_PAUSED	NA	NA	0.86	160.57	1.55	121.168
ERROR	NA	NA	NA	NA	0.66	77.34
Total Successful Operation Time (seconds)	18,082.82		16,920.44		7,499.86	
Total Successful Operation Percentage	99.93		91.05		97.93	

1 mph. Therefore, the ATMA system was not able to be implemented in the crack sealing operations.

Second, the GPS loss caused system failures still occasionally happened during the open road test. Figure 3.3 shows an example of the ATMA log that recorded the time of error due to GPS loss (i.e., ASTOP_ECRUMB_ERROR state in the third column). Figure 3.4 shows the location where GPS loss occurred under an overpass. However, the system should remain operational within 30s of GPS loss instead of going into the "ASTOP_ECRUMB_ERROR" state.

Third, the ATMA only follows certain desired gap when operating, which may cause traffic rule violations. For example, in the trash pickup operation, as shown in Figure 3.5, the ATMA stopped in the middle of the intersection when the leader truck stopped to pick up trash. However, such stops should be avoided.

3.3 INDOT Worker's Perception of ATMA System

A survey is designed to study INDOT workers' perception of the ATMA system after the closed road and open road test. The survey covers demographic

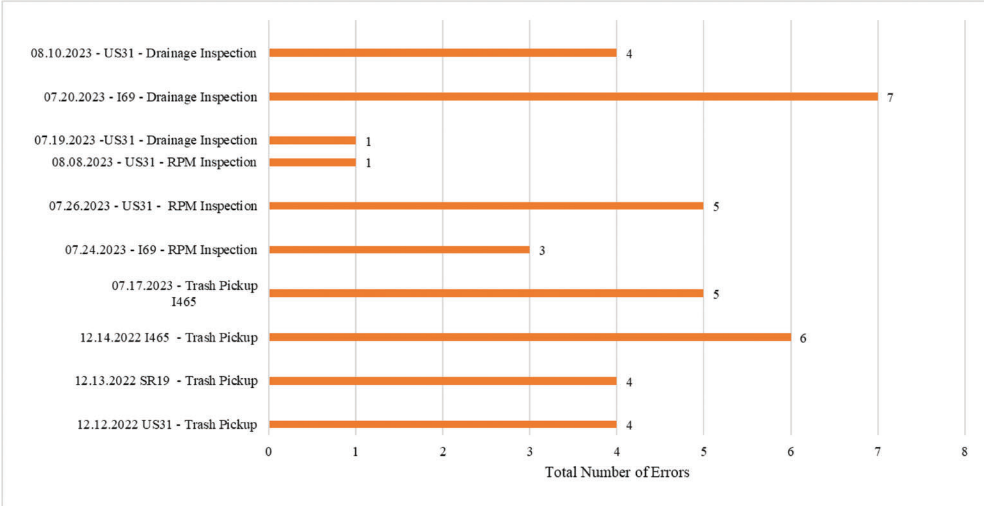

Figure 3.1 Total number of errors each day.

Figure 3.2 The ATMA system remained on "stop" during crack sealing operations.

information, an evaluation of the ATMA user interface, an evaluation of ATMA system function, an evaluation of the ATMA system's impact on safety and productivity, and additional comments. The survey is attached in Appendix C for reference.

3.3.1 Demographic Information

In total, 14 participants are collected in the survey, with 8 of them from the Tipton unit and 5 from the Indy unit. Table 3.6 summarizes participants' demographic information, which shows that workers from both Tipton and Indy units are experienced in crack sealing, trash pickup, RPM inspection, and underdrain inspection.

The Tipton team participated in 11 days in the ATMA open road test with multiple activities, and the Indy team participated in 2 days of open road test with only the trash pickup activity. The Tipton team had more experience than the Indy team since it had more days of exposure to the ATMA system.

3.3.2 Overall Evaluation of the ATMA system

The workers were asked to give a score for each item in the survey on a scale of 1 (fully disagree) to 5 (fully agree). Overall, workers from both Tipton and Indy groups think the ATMA system can improve their productivity and safety for most mobile work zone operations other than crack sealing as shown in

26:57.1	LDU	RUN	DEADRECI	14265710	0	22895	145	39.99074	-85.9242
26:57.2	FLW	RUN	READY	14265720	22945	22895	145	39.99066	-85.9247
26:57.2	LDU	RUN	DEADRECI	14265720	0	22895	145	39.99074	-85.9242
26:57.3	FLW	RUN	READY	14265730	22945	22895	145	39.99066	-85.9247
26:57.4	FLW	ASTOP_EC	READY	14265740	22945	22895	145	39.99066	-85.9247
26:57.4	LDU	RUN	DEADRECI	14265740	0	22895	145	39.99074	-85.9242
26:57.5	FLW	ASTOP_EC	READY	14265750	22945	0	0	39.99066	-85.9247
26:57.5	LDU	RUN	DEADRECI	14265750	0	0	0	39.99074	-85.9242
26:57.6	FLW	ASTOP_EC	READY	14265760	22945	0	0	39.99066	-85.9247
26:57.6	LDU	RUN	DEADRECI	14265760	0	0	0	39.99074	-85.9242
26:57.7	FLW	ASTOP_EC	READY	14265770	22945	0	0	39.99066	-85.9247
26:57.7	LDU	RUN	DEADRECI	14265770	0	0	0	39.99074	-85.9242
26:57.8	FLW	ASTOP_EC	READY	14265780	22945	0	0	39.99066	-85.9247
26:57.9	LDU	RUN	DEADRECI	14265780	0	0	0	39.99074	-85.9242
26:57.9	FLW	ASTOP_EC	READY	14265790	22945	0	0	39.99066	-85.9247
26:58.0	LDU	RUN	DEADRECI	14265790	0	0	0	39.99074	-85.9242
26:58.0	FLW	ASTOP_EC	READY	14265790	22945	0	0	39.99066	-85.9247
26:58.0	FLW	ASTOP_EC	READY	14265800	22945	0	0	39.99066	-85.9247

Figure 3.3 ATMA log showing error due to GPS loss.

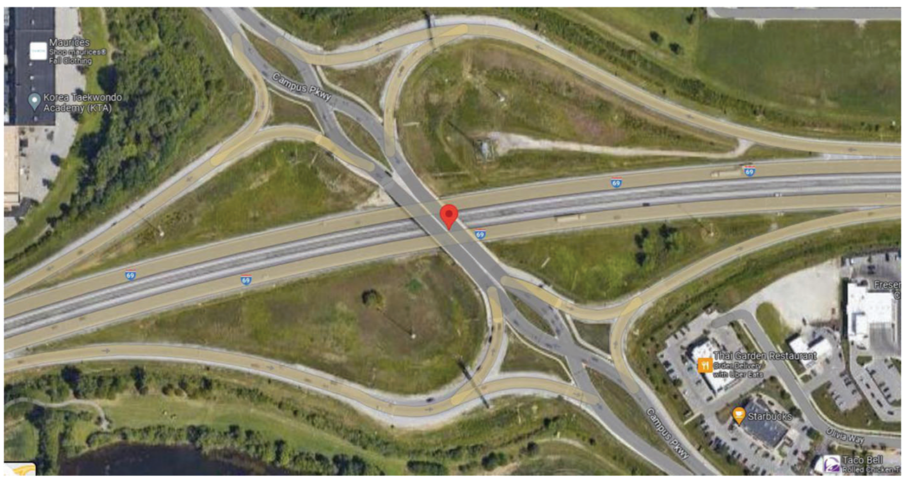

Figure 3.4 The location where the GPS loss happened.

Figure 3.5 ATMA stopped in the middle of the intersection.

TABLE 3.6
Demographic information of participants

	Tipton (years)	Indy (years)	All (years)
How long have you worked for INDOT?	16.56	10.67	14.04
How long have you worked for crack sealing?	16.44	9.17	13.32
How long have you worked for pothole patching?	16.44	9.17	13.32
How long have you worked for trash pickup?	16.44	9.17	13.32
How long have you worked for raised pavement marker (RPM) inspection?	16	9.17	13.07
How long have you worked for underdrain inspection?	16.44	9.17	13.32

TABLE 3.7
Workers' evaluation of the ATMA system's impact on productivity

	Tipton	Indy	All	p-value
My productivity is improved for *crack sealing* operations when ATMA is used, compared with TMA.	2.00	2.80	2.31	0.126
My productivity is improved for *pothole patching* operations when ATMA is used.	3.38	2.80	3.15	0.140
My productivity is improved for *trash pickup* operation when ATMA is used.	3.88	3.20	3.62	0.137
My productivity is improved for *underdrain inspection* operations when ATMA is used.	3.88	3.00	3.54	0.092
My productivity is improved for *RPM inspection* operations when ATMA is used.	3.75	3.00	3.46	0.130

TABLE 3.8
Workers' evaluation of ATMA system's impact on safety

	Tipton	Indy	All	p-value
Using ATMA system for *crack sealing* operations is safer than using TMA.	1.75	3.00	2.23	**0.028**
Using ATMA system for *pothole patching* operations is safer than using TMA.	3.00	2.60	2.85	0.281
Using ATMA system for *trash pickup* operations is safer than using TMA.	3.88	2.80	3.46	0.059
Using ATMA system for *underdrain inspection* operations is safer than using TMA.	4.00	2.80	3.54	0.029
Using ATMA system for *RPM inspection* operations is safer than using TMA.	3.88	2.60	3.38	0.037

Table 3.7 and Table 3.8. Failure in the crack sealing operations described above greatly impact the workers' trust in the system.

3.3.3 Factors Impacting Workers' Evaluation of the ATMA System

Two major factors, including age and experience, are considered to be the impact factors of workers' evaluation of the ATMA system. As for experience, the Tipton group is classified as the more experienced group, and the Indy group is classified as the less experienced group. As for age, the workers are classified into the young group (younger than 50 years old), and the old group (older than 50 years old). In total, eight people are classified into the young group and six people are classified into the old group.

3.3.3.1 Impact of workers' experience on the evaluation. The results indicate that workers with more experience operating the ATMA system have higher evaluations of the ATMA system. Table 3.9 shows Tipton team has a significantly higher evaluation of the ATMA system's ability to be operated automatically on all types of roads than the Indy team. Table 3.10 further indicates that the Tipton team, with more experience using the ATMA system, has a higher evaluation of the ATMA system's ability to be operated in various cases, such as passing overhead bridges, passing traffic signals, passing roundabouts, passing stop-sign intersections, and changing lane. Table 3.11 shows workers' evaluation of the ATMA system's ability under extreme cases. Workers with more experience have a higher evaluation of the ATMA system's ability to operate successfully under those extreme cases.

3.3.3.2 Impact of workers' age on the evaluation. The null hypothesis is that young workers have a higher evaluation of the ATMA system than old workers

TABLE 3.9
Workers' evaluation of ATMA system's ability to operate automatically on different road conditions

	Tipton	Indy	All	p-value
Interstate (e.g., I-465)	4.38	2.33	3.50	**0.001**
Arterial	3.88	2.67	3.36	**0.005**
Trunk Highway (e.g., US-31)	4.50	3.00	3.86	**0.003**
State Road (e.g., SR 19)	4.38	3.00	3.79	**0.004**

Note: Bold numbers indicate statistic significance (<0.05).

TABLE 3.10
Workers' evaluation of ATMA system's ability to operate automatically for various operations

	Tipton	Indy	All	p-value
Passing Overhead Bridge	2.50	1.83	2.21	0.204
Passing Traffic Signal	3.88	2.67	3.36	0.063
Passing Roundabout	3.88	2.00	3.07	**0.011**
Passing Stop-Sign Intersection	3.63	2.17	3.00	**0.021**
Changing Lane	4.00	2.50	3.36	**0.020**

Note: Bold numbers indicate statistic significance (<0.05).

TABLE 3.11
Workers' evaluation of ATMA system's ability to operate automatically under extreme cases

	Tipton	Indy	All	p-value
Automatic Stop	4.63	3.67	4.21	**0.010**
Emergency Stop	4.50	4.00	4.29	0.139
Following Along the Straight Line	4.50	3.17	3.93	**0.007**
Following Along the Slalom Course	3.8	3.00	3.50	**0.013**
Turning (e.g., turn left/right, etc.)	3.88	2.50	3.29	**0.005**
Obstacle Detection	4.50	3.8	4.21	0.088
Vehicle Intrusion	4.25	3.50	3.93	0.067
GPS Downgrade	4.00	3.00	3.57	**0.033**
Sudden Stop with Errors Displayed on User Interface	4.38	3.50	4.00	**0.005**

Note: Bold numbers indicate statistic significance (<0.05).

TABLE 3.12
Workers' evaluation of ATMA system's ability to be operated automatically on different road conditions by age

	Young	Old	All	p-value
Interstate (e.g., I-465)	4.13	2.67	3.50	**0.039**
Arterial	3.75	2.83	3.36	0.064
Trunk Highway (e.g., US-31)	4.13	3.50	3.86	0.311
State Road (e.g., SR 19)	4.13	3.33	3.79	0.172

Note: Bold numbers indicate statistic significance (<0.05).

because young people usually have a shorter learning curve and higher acceptance of new technologies Interestingly, we find that age does not impact their evaluation of the ATMA system significantly as shown in Tables 3.12, 3.13, and 3.14. The results only show that young workers have significantly higher evaluations of the ATMA system on its ability to operate on interstate highways. Otherwise, no significant difference is found between young and old drivers.

3.3.4 Summary

Key findings of the workers' survey are summarized below.

- Generally, INDOT workers think ATMA can improve their productivity and safety for work zone operations under which the ATMA can be successfully implemented. Since the ATMA failed in the crack sealing operations, the workers' evaluation is low.

TABLE 3.13
Workers' evaluation of ATMA system's ability to be operated automatically for various operations by age

	Young	Old	All	p-value
Passing Overhead Bridge	2.38	2.00	2.21	0.322
Passing Traffic Signal	3.50	3.17	3.36	0.344
Passing Roundabout	3.13	3.00	3.07	0.446
Passing Stop-Sign Intersection	3.25	2.67	3.00	0.224
Changing Lane	3.38	3.33	3.36	0.479

TABLE 3.14
Workers' evaluation of ATMA system's ability to be operated automatically under extreme cases by age

	Young	Old	All	p-value
Automatic Stop	4.38	4.00	4.21	0.204
Emergency Stop	4.25	4.33	4.29	0.430
Following Along Straight Line	4.13	3.67	3.93	0.225
Following Along Slalom Course	3.63	3.33	3.50	0.250
Turning (e.g., turn left/right, etc.)	3.75	2.67	3.29	**0.028**
Obstacle Detection	4.50	3.83	4.21	0.088
Vehicle Intrusion	4.00	3.83	3.93	0.375
GPS Downgrade	3.88	3.17	3.57	0.104
Sudden Stop with Errors Displayed on a User Interface	4.38	3.50	4.00	0.005

Note: Bold numbers indicate statistic significance (<0.05).

- Workers who have more experience using the ATMA system have a higher evaluation. Therefore, providing more training and practice is an effective way to improve workers' acceptance of adopting this technology.
- Age is not a key factor affecting workers' confidence in operating the ATMA system, though young people are relatively more confident than old ones.

4. ATMA SYSTEM SIMULATION EVALUATION

4.1 Introduction

Since the ATMA is operated at significantly lower speeds than surrounding traffic, it serves as a moving bottleneck on the road and may have a significant impact on mobility. To quantify the mobility impact, microscopic traffic simulation models using VISSIM are constructed to mimic ATAM operations under various traffic demand levels and roadway types.

4.2 Simulation Setup and Analysis

VISSIM is selected as the microscopic software for traffic simulation. The same roadway segments as in the field deployment are selected, which are interstate highway I-465, trunk highway US-31, and state road SR 19. Two variables are considered in the analysis, which are ATMA operation speeds (i.e., 2 mph, 5 mph, 10 mph, and 20 mph), and traffic demand levels (80% of peak hour demand, 100% of peak hour demand, and 120% of peak hour demand). In total, we consider 13 scenarios for each road type including one baseline without deployment of the ATMA system, as shown in Table 4.1. The traffic data (e.g., volume, average speed, and vehicle composition) provided by the INDOT traffic count database system (https://indot.public.ms2soft.com/tcds/tsearch.asp?loc=Indot&mod) is used for simulation model calibration.

TABLE 4.1
All scenarios for the VISSIM simulation

	With ATMA	ATMA Speed	Traffic Demand
0 (Baseline)	No	NA	X1
1	Yes	2 mph	X0.8
2	Yes	2 mph	X1
3	Yes	2 mph	X1.2
4	Yes	5 mph	X0.8
5	Yes	5 mph	X1
6	Yes	5 mph	X1.2
7	Yes	10 mph	X0.8
8	Yes	10 mph	X1
9	Yes	10 mph	X1.2
10	Yes	20 mph	X0.8
11	Yes	20 mph	X1
12	Yes	20 mph	X1.2

The leader and follower trucks are loaded from an on-ramp located at one end of the road segment. The speed of the leader truck is set as 2 mph, 5 mph, 10 mph, and 20 mph for different scenarios. The VISSIM external driver model DLL is used to control the follower truck following the leader truck with a commanded gap of 150 feet. A proportional-derivative (PD) controller is coded to control the follower truck's speed. Each simulation is executed for 3,600 seconds and the average of three simulation runs are used as the final results.

4.2.1 Simulation Analysis for I-465

Figure 4.1 shows the road segment of I-465 in Google Maps and the simulated road geometry in VISSIM. Two cases are simulated for I-465. Case 1 assumes that drivers follow the post-speed limit, which is 55 mph for the car and 45 mph for the truck. Case 2 assumes a more realistic vehicle speed, where the cars are driven at an average of 70 mph, and trucks are driven at an average of 60 mph.

Figure 4.2 and Figure 4.3 show the traffic delay for I-465 for cases 1 and 2, respectively. Both cases indicated that the vehicle delay increases with increasing traffic demand and lower ATMA operation speed. Especially under 2 mph of ATMA operation speeds and higher demand levels (scenarios 2 and 3), passing the single moving bottleneck can take more than 3 mins.

4.2.2 Simulation Analysis on US-31

Figure 4.4 shows the road segment of US-31 in Google Maps and the simulated road geometry in

Figure 4.1 Simulated section of I-465 in Google Maps (left) and VISSIM (right).

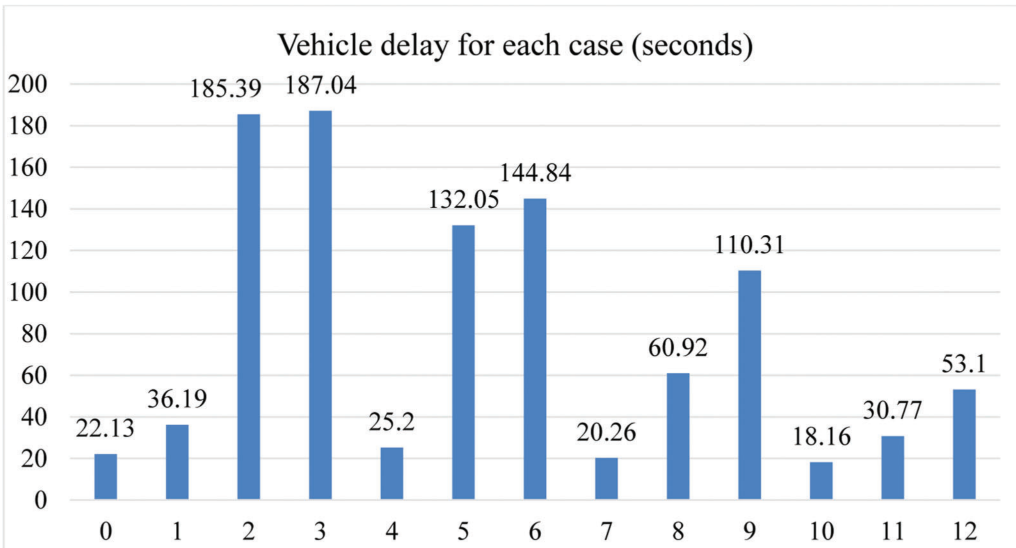

Figure 4.2 Traffic delay results for I-465: case 1.

VISSIM. It is assumed that drivers follow the post-speed limit, which is 60 mph for the car and 50 mph for the truck. Results show the traffic delay results for US-31 for all scenarios. The results indicate that higher traffic volume leads to longer traffic delays, and faster ATMA operation speed can reduce the traffic delay as shown in Figure 4.5. The delay patterns are similar to those on the interstate highway. Due to lower traffic demand in US-31, the overall impact of the ATMA operation on mobility is also much lower.

4.2.3 Simulation Analysis on SR 19

Figure 4.6 shows the road segment of SR 19 in Google Maps and the simulated road geometry in VISSIM. The real speed distribution data provided by INDOT traffic count database system is used to code the speed distribution in the VISSIM simulation as shown in Figure 4.7. Different from the other two scenarios, SR 19 is a two-lane highway, which means other vehicles can only borrow the lane from the opposite direction to pass the moving bottleneck.

Figure 4.8 shows the traffic delay for SR 19. A similar pattern is found, which is higher traffic volume and slower ATMA operation speed lead to higher traffic delay. The actual demand for SR 19 is even lower than US-31. However, due to the characteristics of a two-lane highway, the delay impact is higher.

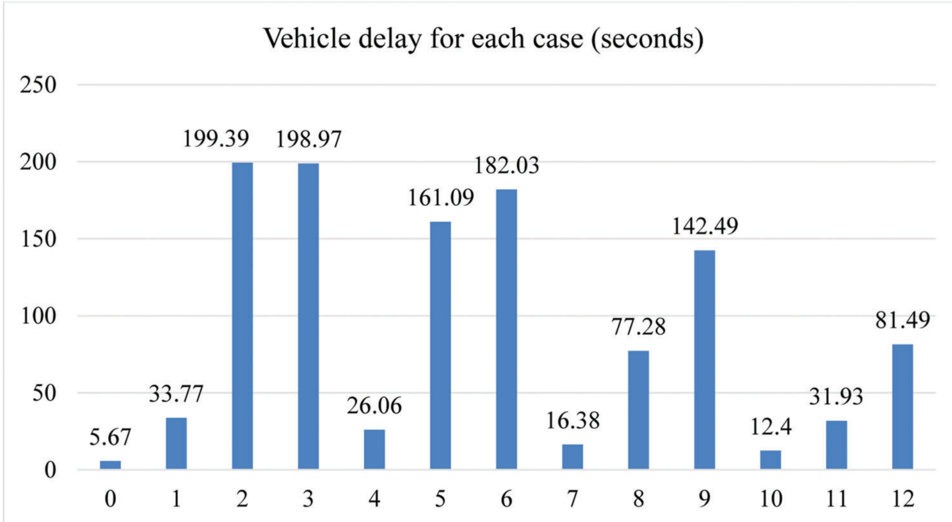

Figure 4.3 Traffic delay results for I-465: case 2.

Figure 4.4 Simulated section of US-31 in Google Maps (left) and VISSIM (right).

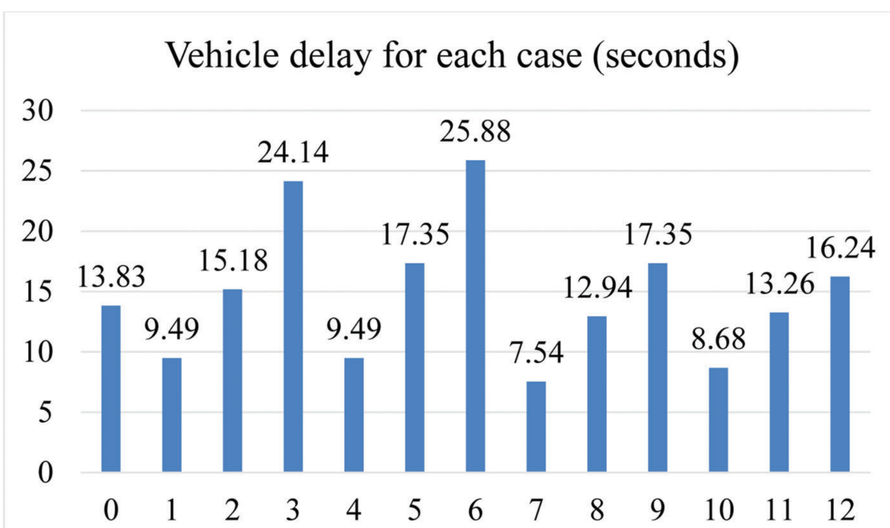

Figure 4.5 Traffic delay results for US-31.

Figure 4.6 Simulated section of SR 19 in Google Maps (left) and VISSIM (right).

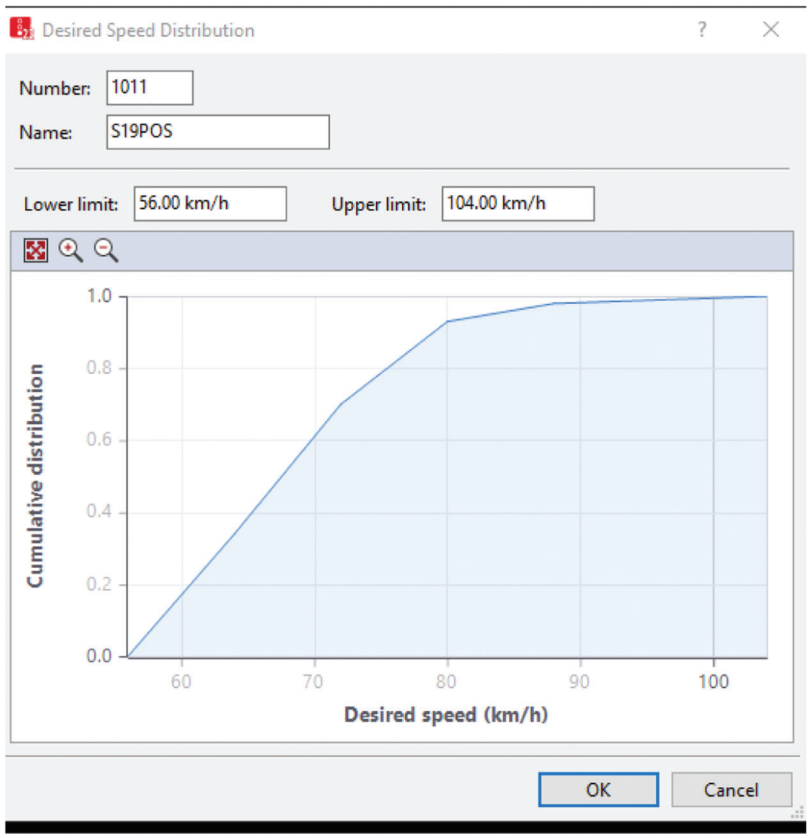

Figure 4.7 Car speed distribution on SR 19.

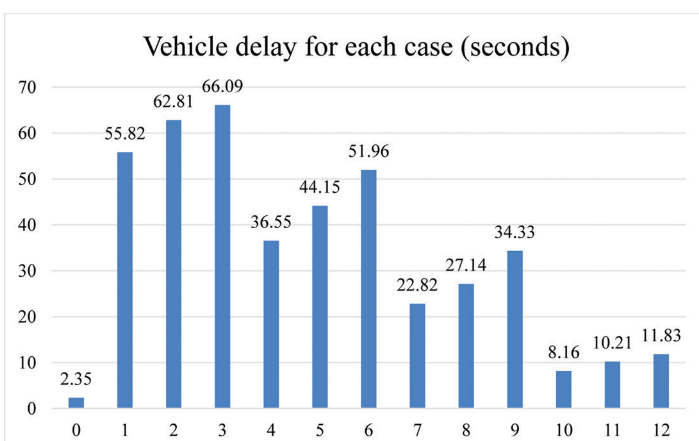

Figure 4.8 Traffic delay results for SR 19.

5. COST-BENEFIT ANALYSIS

While the ATMA system has demonstrated significant benefits in saving transportation workers' lives and reducing their risk of injuries, the cost of the system is another critical factor for DOTs. This section aims to provide a cost-benefit analysis based on the cost of purchase and maintenance of the ATMA system and the benefits of using the ATMA system.

5.1 Methodology

The methodology and tool used for the cost-benefit analysis are adapted from the FDOT's ATMA report (Agarwal et al., 2021). The data to calculate the cost and benefit of the ATMA system includes:

- TMA Crashes
  - The average number of TMA-related crashes per year: 21.8 (INDOT, n.d.).
  - Average number of fatal/injury TMA crashes involved agency's workers: 4.83 (INDOT, n.d.).
- Agency Size
  - The average daily number of active TMAs on the road in INDOT: 50 (an estimated number).
  - Percentage of ATMAs in your agency: 2% (assuming one ATMA).
- System Cost and Characteristics
  - TMA expected life cycle (in years): 10 (INDOT, n.d.).
  - Leader truck cost: 0 (assuming INDOT provides the leader truck).
  - Follower truck cost: 0 (assuming INDOT provides the follower truck).
  - Technology procurement cost: $250,000 (from Kratos).
  - Deployment, training and one-time fee: $120,000 (only applies to the first-time deployment) (from Kratos).
  - Yearly maintenance cost: $0–$100,000 (from Kratos).

The cost for the first-time deployment is calculated in the following equation.

$$Total\ cost\ of\ ATMA = Leader\ truck\ cost + Follower\ truck\ cost + Technology\ procurement\ cost + Deployment, training\ and\ one\text{-}time\ free + Yearly\ maintenance\ cost \times TMA\ expected\ life\ cycle$$

The cost for further deployment is calculated in the following equation.

$$Total\ cost\ of\ ATMA = Leader\ truck\ cost + Follower\ truck\ cost + Technology\ procurement\ cost + Yearly\ maintenance\ cost \times TMA\ expected\ life\ cycle$$

The system benefit of ATMA (crash cost) is calculated below.

TABLE 5.1
Indiana crash statistics (Indiana Criminal Justice Institute, n.d.)

Year	Total	Fatal	Nonfatal
2020	175,816	808 (0.5%)	26,303 (15.0%)
2019	217,387	739 (0.3%)	31,194 (14.3%)
2018	217,077	789 (0.4%)	32,383 (14.9%)
2017	219,105	834 (0.4%)	34,219 (15.6%)
2016	223,734	821 (0.4%)	48,781 (21.8%)
Average	*210,624*	*798 (0.4%)*	*34,576 (16.4%)*

TABLE 5.2
Crash cost (https://safety.fhwa.dot.gov/hsip/docs/fhwasa17071.pdf)

Severity	Comprehensive Crash Unit Cost in 2013 Dollars
K (Fatal)	$9,100,000
A/B/C (Injury)	$955,500
O (Property only)	$27,300

Table 5.1 shows the Indiana crash statistics from 2016 to 2020, and Table 5.2 describes the crash cost in 2013 dollars. The total crash cost in 2013 dollars is calculated in the following equation.

$$Total\ crash\ cost = \$9{,}100{,}000 \times 0.004 + \$955{,}500 \times 0.164 = \$193{,}102$$

Note that crashes that only involve property damage are excluded from the calculation because the main benefit of the ATMA system is to reduce workers' fatality/injury. The cost is converted to 2023 dollars based on the CPI inflation calculator provided by the Bureau of Labor Statistics (n.d.). The total crash cost in 2023 dollars is $254,488.

The fatality/injury crash cost saved by ATMA per year is calculated in the following equation.

$$Injury\ crash\ cost\ saved\ by\ ATMA\ per\ year = \frac{Total\ crash\ cost \times Number\ of\ ATMA}{The\ number\ of\ active\ TMAs\ in\ INDOT}$$

Then, the present value of cost is calculated in the following equation.

$$Present\ value\ of\ cost = Annuity\ factor \times Injury\ crash\ cost\ saved\ by\ ATMA\ per\ year$$

Finally, the benefit-to-cost ratio is calculated in the following equation.

$$Benefit\ to\ cost\ ratio = \frac{Present\ value\ of\ cost}{Total\ cost\ of\ ATMA}$$

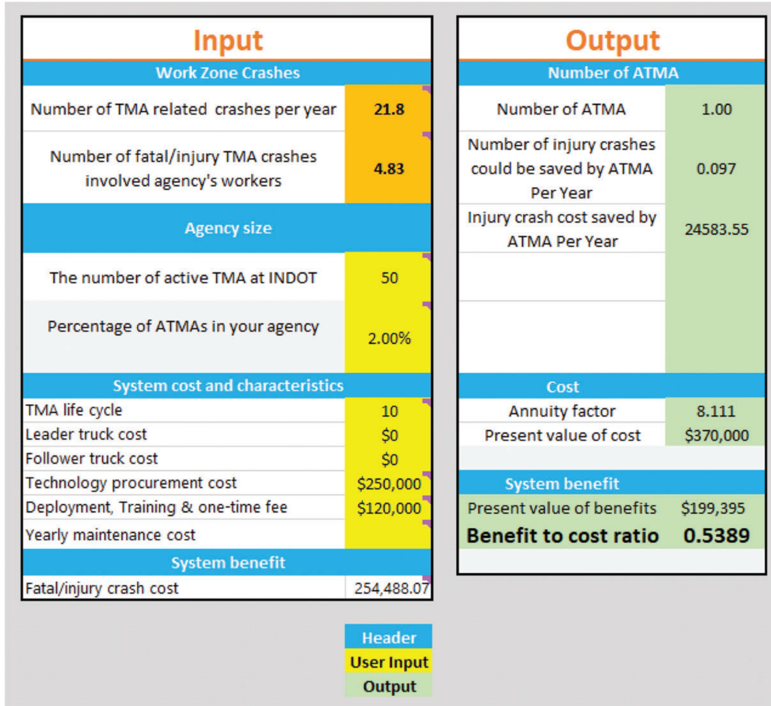

Figure 5.1 Cost-benefit analysis results: first-time deployment.

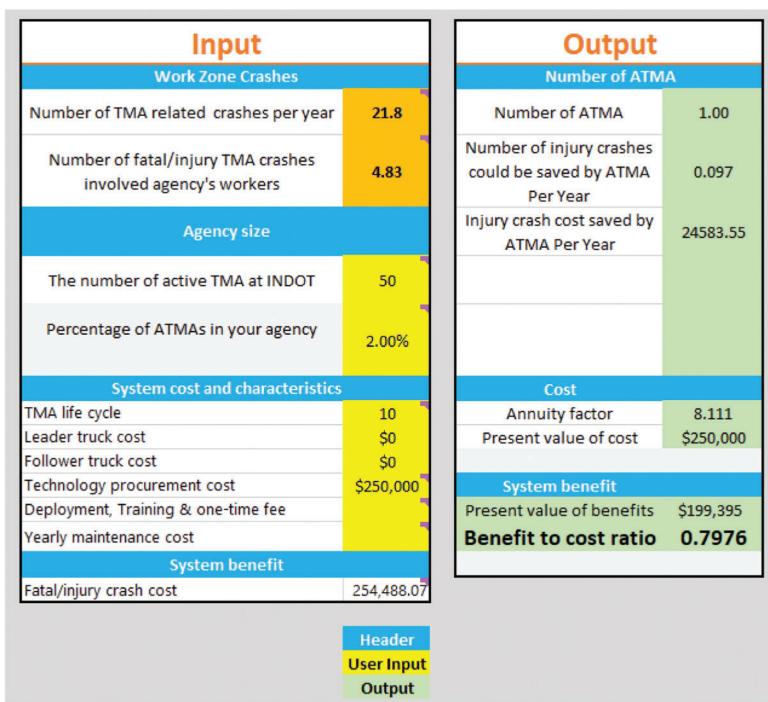

Figure 5.2 Cost-benefit analysis results: future deployment.

5.2 Cost-Benefit Analysis Results

Based on the collected data and methodology, the cost-benefit analysis results for the ATMA deployment in Indiana are shown in Figure 5.1 and Figure 5.2, respectively. Figure 5.1 shows the results for the first-time deployment and Figure 5.2 shows the results for further deployment where the one-time fee is waived. In both cases, the benefit-cost ratios are smaller than 1.0, mainly due to the high procurement and maintenance cost of the technology. It is also related to the relatively low crash statistics in Indiana, compared to other states such as Florida (Agarwal et al., 2021).

6. CONCLUSIONS AND RECOMMENDATIONS

As an emerging technology, the ATMA system has been developed and deployed in the past few years. In this project, we systematically reviewed, tested, and evaluated the ATMA system in both simulation and real-world environments under various operating scenarios, traffic conditions, and mobile work zone operations. This section summarizes the findings from the ATMA test in Indiana and provides recommendations from several perspectives.

First, the ATMA system can be successfully deployed for selected mobile work zone operations, such as sweeping, trash pickup, RPM inspection, and underdrain inspection. However, some activities may not be suitable (e.g., permanent pothole patching) or doable (e.g., crack sealing). The preferred activities for ATMA operations should (1) have continuous movement, and (2) have a moving speed beyond 5 mph.

Second, the ATMA system can be operated for most of the time under various road types and traffic conditions. However, system failure caused by GPS loss is still a critical issue that requires further system upgrades.

Third, the current ATMA system only follows the leader truck with a predefined gap and does not have the capability to understand different traffic scenarios and traffic rules. Therefore, when deploying the ATMA system, additional training should be provided to the leader truck's driver.

Fourth, the participating workers welcome this technology in general. The more the workers operate it, the more trust the workers have in the system. However, frequent system failure may greatly reduce the workers' trust and desire to operate the system.

Fifth, the operation of the ATMA system may cause extra delays to general traffic. When and where to deploy this technology need consideration (e.g., below certain AADT or avoid peak hours).

Finally, the current cost of the technology does not make a strong business case for purchasing the system. It is expected that the price may decrease significantly in the future with more mature technology level and increased market size. It is also interesting to explore other deployment options such as rental.

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APPENDICES

Appendix A. Semi-Structured Interview: Questions for State DOTS and Universities

Appendix B. Closed Road Test Results

Appendix C. Workers' Perception of the ATMA System

APPENDIX A. SEMI-STRUCTURED INTERVIEW: QUESTIONS FOR STATE DOTS AND UNIVERSITIES

Part 1: The Current Implementation of **ATMA System** in DOTs

1. Can you share with us your experience with ATMA?

1.1. Did you rent or purchase the ATMA?

1.2. What on-site operations / tasks have your DOT worked with ATMA?

1.3. What open-road operations have your DOT worked with ATMA?

1.4. Under what road types / lighting conditions / traffic flow have your DOT worked with ATMA?

1.5. How many ATMA does your DOT own?

1.6. How many years have your DOT worked with ATMA?

2. What is difference between TMA and ATMA during work zone operation?

3. What are the benefits of using ATMA?

4. What are the challenges that you have encountered with ATMA?

5. What is your DOT's plan for ATMA implementation in the future?

6. ATMA System

6.1. Does the ATMA system meet your expectations during normal operation and emergency situations?

6.2. What is the impact of ATMA on traffic safety?

6.3. What is the impact of ATMA on traffic mobility?

6.4. What is the impact of ATMA on cost?

Part 2: **Workers**' Perception/Trust, Action, and Productivity about ATMA

1. What is workers' perception of ATMA?

2. What is workers' level of trust on ATMA? 1, 2, 3, 4, 5

3. What is workers' behavior change around ATMA?

4. What is workers' productivity change around ATMA?

5. What is the preference of your workers between TMA and ATMA?

6. Have you workers experienced any emergency around ATMA? If yes, please specify more details about workers' perception, action, and interaction with the ATMA under emergency situation.

Part 3: Comments

1. Have you collected any data related to ATMA, TMA, or workers during the test and deployment of ATMA?

2. Could you share with us?

3. Do you have any other comments?

APPENDIX B. CLOSED ROAD TEST RESULTS

The section documents the closed road test results for each case and is organized by each focus area. The test procedure and result for each case are described in detail. A video highlighting the closed road-testing results can be found at this link https://www.youtube.com/watch?v=fo8CJCIGr_Y.

B.1 Focus Area 1: Safety

Test Case 1: Functionality Inspection

Table B.1. Test Procedure-Test Case 1

Operation procedure	• Inspected if the installed ATMA system, such as the user interface (UI) table computer, emergency stop buttons, and sensors interfered with normal operations. • Inspected if the UI tablet computer in the leader vehicle was easy to operate. • Checked the radar and Lidar of the ATMA system were functional. • Checked if the turn signals of the follower vehicle were coordinated with the leader vehicle. • Conducted 3 runs for each side of turn signals.
Data collection	• Recorded if the ATMA passed the functionality inspection.
Expected results	• The installed ATMA system should not interfere normal operations of the leader and follower trucks. • The UI table computer should be easy to operate. • The Radar and Lidar sensors should work properly. • The turn signals of the follower vehicle should be coordinated with the leader vehicle.
Total number of runs	• 6 runs for turn signal inspection and 1 run for other inspections

The ATMA system passed the functionality inspection listed in Table B.2 and Table B.3.

Table B.2 Data Collection Form 1-Test Case 1

	Yes/No
If UI table computer interferers normal operation	No
If emergency stop buttons interferers normal operation	No
If sensors interferers normal operation	No
If UI table computer is easy to operate	Yes
If Lidar works properly	Yes
If radar works properly	Yes

Table B.3 Data Collection Form 2-Test Case 1

Runs	Side	Turn Signal Coordinated (Yes/No)
1	Left	Yes
2	Left	Yes
3	Left	Yes
4	Right	Yes
5	Right	Yes
6	Right	Yes

Test Case 2: Automatic Stop (A-stop)–Leader Vehicle Internal Button (OCU)

Table B.4 Test Procedure-Test Case 2

Operation procedure	• Placed three lines of traffic cones in the center of the road and on both edges of the road. Each line had three traffic cones with 20 feet spacing. • Activated the leader truck and ATMA. • Commanded the gap between the leader truck and ATMA to 100 feet. • Drove the leader truck in a straight line at 5 mph. • Initiated "stop" command when the front of ATMA passed traffic cones in the middle column. • Activated A-stop inside the leader vehicle. • Conducted 3 runs for each speed. • Repeated at 10 mph and 15 mph.
Data collection	• Measured the time between stop command initiation and ATMA stopped by stopwatch. • Measured the distance between the marked position and the ATMA stop location with a measuring wheel. • Checked engine status.
Expected results	The ATMA should stop after A-stop initiation.
Total number of runs	9 runs

The time to stop after A-stop initiation and distance traveled after A-stop initiation were calculated from the ATMA log files. The results are shown in Table B.5. The engine was still on after a-stop initiation which was consistent with the ATMA system design.

Table B.5 Data Collection Form-Test Case 2

Runs	Test Speed	ATMA Stop or Not (Yes/No)	Time to Stop after A-stop initiation (sec)	Distance Travelled after A-stop Initiation (feet)	Status of Engine after A-stop Initiation (on/off)
1	5 mph	Yes	3.35	7.12	On
2	5 mph	Yes	2.81	16.8	On
3	5 mph	Yes	1.41	7.24	On
4	10 mph	Yes	4.30	29.23	On
5	10 mph	Yes	4.30	27.74	On
6	10 mph	Yes	3.60	22.62	On
7	15 mph	Yes	4.30	48.08	On
8	15 mph	Yes	4.60	57.63	On
9	15 mph	Yes	3.90	38.17	On

Test Case 3: E-Stop–ATMA Internal Button

Table B.6 Test Procedure-Test Case 3

Operation procedure	• Placed three lines of traffic cones in the center of the road and on both edges of the road. Each line had three traffic cones with 20 feet spacing. • Activated the leader truck and ATMA. • Commanded the gap between the leader truck and ATMA to 100 feet. • Drove the leader truck in a straight line at 5 mph. • Initiated "stop" command when the front of ATMA passed traffic cones in the middle column. • Activated E-stop inside the ATMA. • Conducted 3 runs for each speed. • Repeated at 10 mph and 15 mph.
Data collection	• Measured the time between stop command initiation and ATMA stopped by stopwatch. • Measured the distance between the marked position and the ATMA stop location with a measuring wheel. • Checked engine status.
Expected results	The ATMA should stop after E-stop initiation.
Total number of runs	9 runs

Since the initiation of the E-stop loses the current ATMA log file, the required ATMA log files to calculate the time to stop after E-stop initiation and distance traveled after E-stop initiation were not saved. Therefore, this information for E-stop-related cases such as cases 3–5 was measured by stopwatch and measuring wheel. The related information to case 3 was shown in Table B.7. The engine was off for all E-stop runs. This was consistent with the ATMA system design.

Table B.7 Data Collection Form-Test Case 3

Runs	Test Speed	ATMA Stop or Not (Yes/No)	Time to Stop after E-stop initiation (sec)	Distance Travelled after E-stop Initiation (feet)	Status of Engine after E-stop Initiation (on/off)
1	5 mph	Yes	3.22	19.2	off
2	5 mph	Yes	3.00	16.0	off
3	5 mph	Yes	3.15	17.9	off
4	10 mph	Yes	3.69	34.5	off
5	10 mph	Yes	3.19	44.0	off
6	10 mph	Yes	3.56	31.0	off
7	15 mph	Yes	3.59	54.1	off
8	15 mph	Yes	4.09	58.11	off
9	15 mph	Yes	3.87	53.7	off

Test Case 4: E-Stop–Emergency Stop/ATMA External Button

Table B.8 Test Procedure-Test Case 4

Operation procedure	• Placed three lines of traffic cones in the center of the road and on both edges of the road. Each line had three traffic cones with 20 feet spacing. • Activated the leader truck and ATMA. • Commanded the gap between the leader truck and ATMA to 100 feet. • Drove the leader truck in a straight line at 5 mph. • Initiated "stop" command when the front of ATMA passed traffic cones in the middle column. • Activated E-stop outside of the ATMA by the worker when ATMA passes the marked position. • Conduct 3 runs.
Data collection	• Measured the time between stop command initiation and ATMA stopped by stopwatch. • Measured the distance between the marked position and the ATMA stop location with a measuring wheel. • Checked engine status.
Expected results	The ATMA should stop after E-stop initiation.
Total number of runs	3 runs

Only 5 mph operations were tested for this case since pushing the E-stop button outside the ATMA was a dangerous case when the speed was high. The results are shown in Table B.9. The engine was off for all runs.

Table B.9 Data Collection Form-Test Case 4

Runs	Test Speed	ATMA Stop or Not (Yes/No)	Time to Stop after E-stop initiation (sec)	Distance Travelled after E-stop Initiation (feet)	Status of Engine after E-stop Initiation (on/off)
1	5 mph	Yes	2.31	20.2	off
2	5 mph	Yes	2.47	11.9	off
3	5 mph	Yes	3.34	15.5	off

Test Case 5: E-Stop–Leader Independent E-stop Button (Initiator)

Table B.10 Test Procedure-Test Case 5

Operation procedure	• Placed three lines of traffic cones in the center of the road and on both edges of the road. Each line had three traffic cones with 20 feet spacing. • Activated the leader truck and ATMA. • Commanded the gap between the leader truck and ATMA to 100 feet. • Drove the leader truck in a straight line at 5 mph. • Initiated “stop” command when the front of ATMA passed traffic cones in the middle column. • Activated E-stop inside the leader truck when ATMA passes the marked position. • Repeated at 10 mph and 15 mph. • Conducted 3 runs for each speed
Data collection	• Measured the time between stop command initiation and ATMA stopped by stopwatch. • Measured the distance between the marked position and the ATMA stop location with a measuring wheel. • Checked engine status.
Expected results	The ATMA should stop after E-stop initiation.
Total number of runs	9 runs

The results for all nine runs under this case are shown in Table B.11.

Table B.11 Data Collection Form-Test Case 5

Runs	Test Speed	ATMA Stop or Not (Yes/No)	Time to Stop after E-stop initiation (sec)	Distance Travelled after E-stop Initiation (feet)	Status of Engine after E-stop Initiation (on/off)
1	5 mph	Yes	3.53	19.3	off
2	5 mph	Yes	3.06	17.3	off
3	5 mph	Yes	3.09	13.1	off
4	10 mph	Yes	3.15	29.1	off
5	10 mph	Yes	3.84	33.2	off

6	10 mph	Yes	3.66	33.8	off
7	15 mph	Yes	3.28	42.1	off
8	15 mph	Yes	3.98	36.3	off
9	15 mph	Yes	4.10	49.5	off

B.2 Focus Area 2: Following Accuracy

Test Case 6: Following Distance Set by User Interface (UI) Panel

Table B.12 Test Procedure-Test Case 6

Operation procedure	• Activated the leader and ATMA and set the gap to 100 feet and drive in a straight line at 5 mph. • Set the gaps to 150, 300, 150 feet, and 100 feet, respectively, after the new gap was stabilized. • Conducted 3 runs for 5 mph.
Data collection	• Collected ATMA log file
Expected results	The ATMA gap can be changed to the new gaps.
Total number of runs	3 runs (2 runs were performed successfully.)

The large gaps for 5mph were not performed which were 500 feet, 750 feet, and 1,000 feet. Similarly, higher speed operations such as 10 mph and 15 mph were not performed. Both were because the space was not large enough.

Also, for the 5-mph operation, only two runs were performed successfully. In the third run, the ATMA operator set the gaps as 100 feet, 150 feet, 300 feet, 150 feet, and 274 feet, which was not consistent with the researcher's requirement.

The gap difference was calculated when each new gap was stabilized by equation (1).

$$\text{Gap difference} = \text{Gap} - \text{Gap (Desired)} \quad \text{(Eq. B.1)}$$

The maximum (max), minimum (min), average and standard deviation (std.) of the gap difference were calculated when the new gap was stabilized as shown in Table B.13. The time to stabilization for each gap change was calculated from the ATMA log files. The results show decreasing the gap took longer than increasing the gap. For example, for both runs, increasing the gap from 150 feet to 300 feet took 16.40 seconds and 16.67 seconds, respectively. However, the decreasing gap from 300 feet to 150 feet took 67.30 seconds and 73.38 seconds, respectively.

Cross track error (CTE) measures the horizontal deviation between ATMA's trajectory and the indented trajectory (Tang et al., 2021). The CTE was provided in log files and recorded at 10 Hz. The ATMA system was designed to meet CTE with an accuracy of ±6 inches (Tang et al., 2021). In this study, the max, min, average, and std. of the CTE were calculated. Table 0-14 shows the CTE for two runs in case 6. The results show the CTE meets the designed requirement.

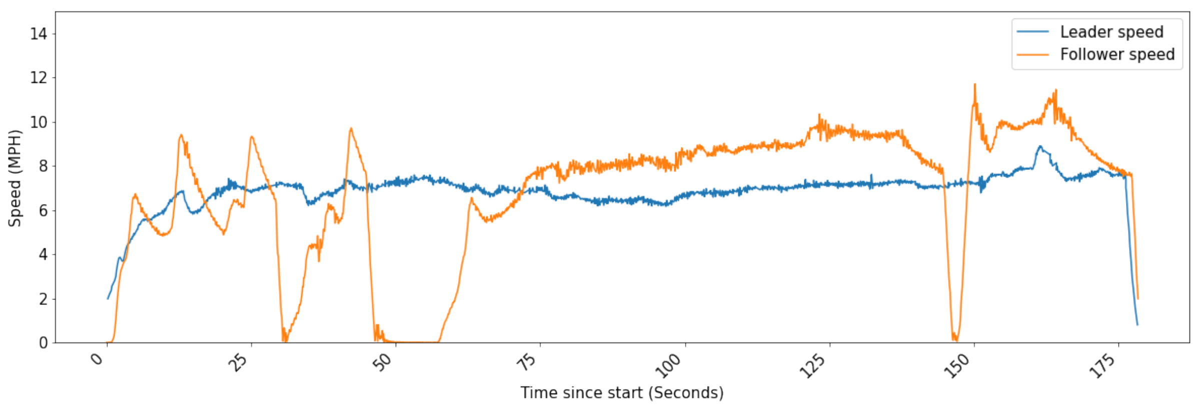
Table B.13 Time taken to stabilization and stabilized accuracy: Case 6

Runs	Speed	Gap Change (feet)	Time Taken to Stabilization (Seconds)	Gap Difference (feet)			
				Max	Min	Average	Std.
1a	5 mph	100 → 150	8.80	5.58	-2.30	2.09	2.30
1b	5 mph	150 → 300	16.40	21.00	-0.33	13.17	5.16
1c	5 mph	300 → 150	67.30	0.66	-13.45	-7.58	4.19
1d	5 mph	150 → 100	24.50	0.00	-4.76	-6.19	3.22
2a	5 mph	100 → 150	9.23	4.59	-2.62	1.68	1.98
2b	5 mph	150 → 300	16.67	21.98	-0.98	12.01	6.57
2c	5 mph	300 → 150	73.38	0.66	-3.94	-2.92	1.19
2d	5 mph	150 → 100	15.58	1.31	-12.14	-4.08	3.14

Table B.14 CTE for each run: Case 6

Runs	CTE (Inches)			
	Max	Min	Average	Std.
1	2.52	-2.52	-0.33	0.74
2	1.97	-1.65	0.019	0.64

Figure B.1 and Figure B.2 and show the speed of the leader and follower trucks, gap and desired gap, and CTE for both two runs. Figure B.1(a) and Figure B.2 (a) show the speed of ATMA was even stopped to increase the gap to the desired one.



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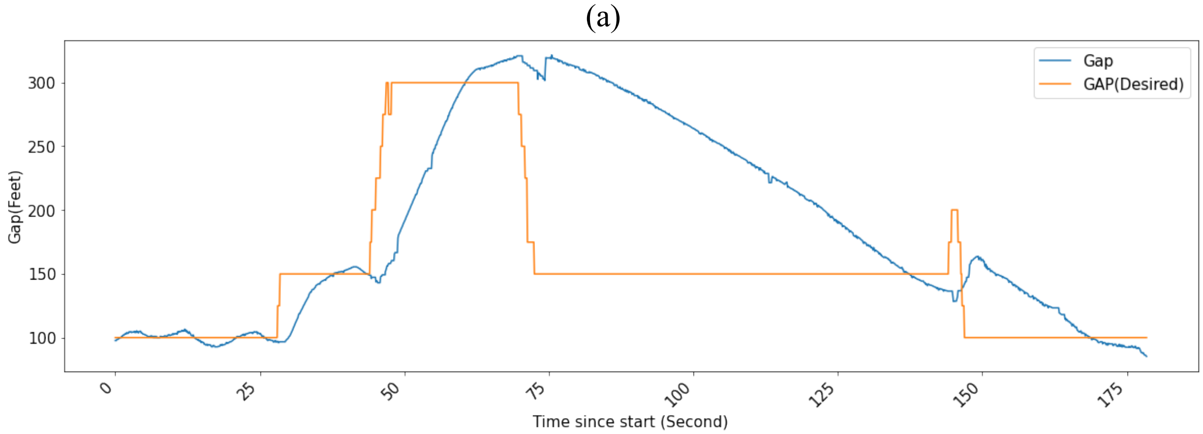

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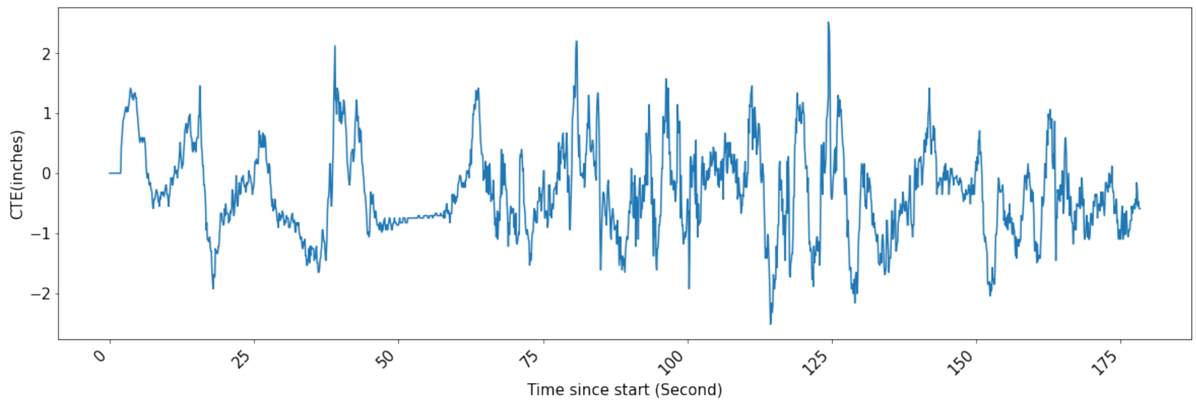

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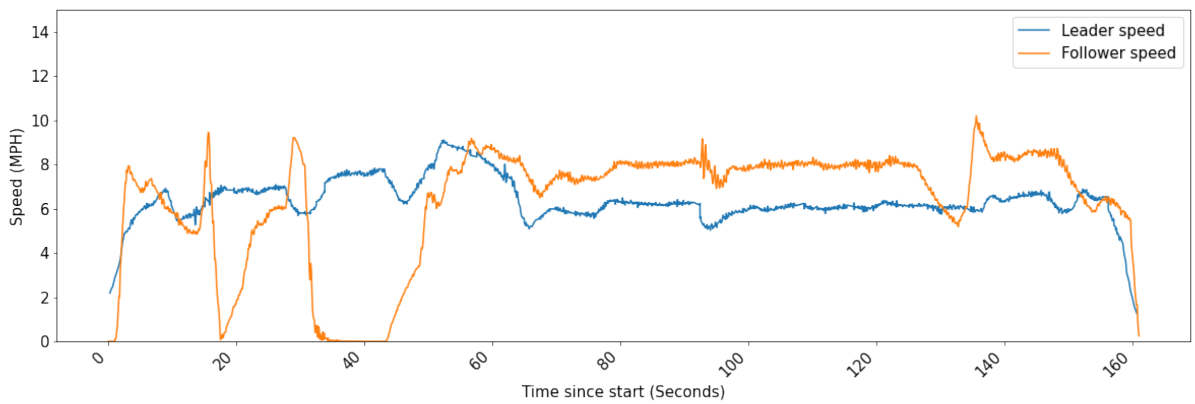
Figure B.1 Test case 6, Run 1: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.



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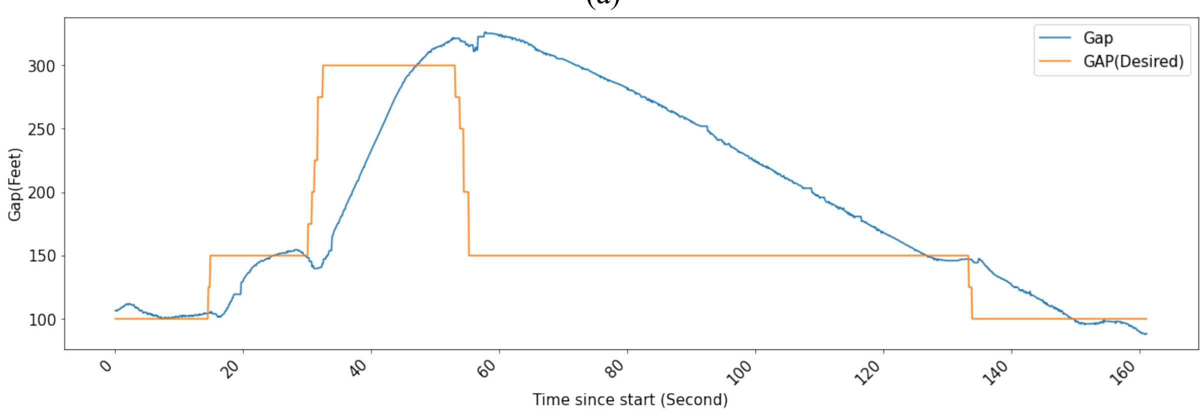

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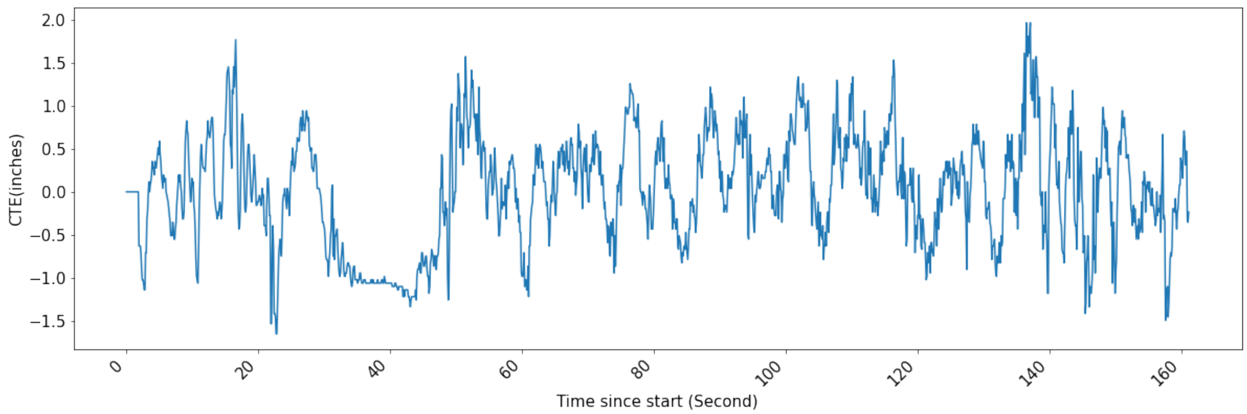


(c)

Figure B.2 Test case 6, Run 2: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.

Test Case 7: Following Accuracy on Straight Line

Table B.15 Test Procedure-Test Case 7

Operation procedure	• Activated the leader truck and ATMA and set the gap to 100 feet and drove in a straight line at 5 mph. • Drove the ATMA in idle mode by a human driver with 100 feet gap in a straight line at 5 mph. The driver was asked to "please drive exactly as the leader truck". • Repeated the test at the speed of 10 mph and 15 mph. • Conducted 3 runs for each speed. • Each run was performed for at least 1,000 feet.
Data collection	• Collected ATMA log files.
Expected results	• The ATMA should maintain the following gap accuracy. • The ATMA should maintain a lateral accuracy of ±6 inches from the leader's path based on the ATMA log file. • The ATMA system should have better following gap accuracy and lateral accuracy when operated autonomously than driven by a human driver.
Total number of runs	6 runs (Each run has three subtasks.)

All six runs were performed successfully. Table B.16 shows the statistics for the gap difference. The results show that under all 10 mph and 15 mph, the automated mode has better performance than the idle mode in terms of all max, min, mean, and std. of gap difference. However, for the 5-mph case, run 2b has better performance than run 1a and 1b in terms of the mean. Run 2c has better performance than run 1a and 1b in terms of std. Table B.17 shows CTE is within the range of ±6 inches. Only the automated model provided CTE, and CTE for idle mode was not recorded. Figure B.3 to Figure B.20. show leader truck speed vs. follower truck speed, gap vs. the desired gap, and CTE for each run.

Table 7.16 Gap difference for each run: Case 7

Runs	Test Speed	Mode	Max (feet)	Min (feet)	Mean (feet)	Std. (feet)
1a	5 mph	Automated	5.249	-44.291	-2.754	8.0318
1b	5 mph	Automated	8.202	-8.8582	-0.418	3.771
1c	5 mph	Automated	6.234	-62.336	-2.528	9.827
2a	5 mph	Idle (human driver)	74.475	18.373	46.118	12.111
2b	5 mph	Idle (human driver)	30.840	-24.934	-2.0176	15.405
2c	5 mph	Idle (human driver)	6.234	-16.076	-4.245	6.302
3a	10 mph	Automated	7.546	-18.701	-1.257	4.896
3b	10 mph	Automated	7.874	-15.420	-1.0560	4.240
3c	10 mph	Automated	6.890	-20.998	-2.157	5.413
4a	10 mph	Idle (human driver)	8.530	-26.903	-2.606	8.021
4b	10 mph	Idle (human driver)	18.0446	-28.543	-6.407	15.844
4c	10 mph	Idle (human driver)	58.399	4.921	41.720	14.565
5a	15 mph	Automated	14.436	-25.919	1.736	7.358
5b	15 mph	Automated	11.483	-10.499	3.311	3.558
5c	15 mph	Automated	14.436	-17.060	2.538	5.876
6a	15 mph	Idle (human driver)	47.572	6.235	35.142	9.133
6b	15 mph	Idle (human driver)	46.916	-0.984	29.528	14.703
6c	15 mph	Idle (human driver)	36.745	0.328	19.825	9.144

Table 7.17 CTE for each run: Case 7

Runs	Test Speed	Mode	CTE (Inches)			
			Max	Min	Average	Std.
1a	5 mph	Automated	3.898	-1.457	0.836	0.688
1b	5 mph	Automated	3.543	-1.772	1.225	0.678
1c	5 mph	Automated	3.307	-1.417	0.697	0.633
3a	10 mph	Automated	4.449	-0.827	1.0584	0.670
3b	10 mph	Automated	3.780	-0.118	1.647	0.788
3c	10 mph	Automated	3.0709	-0.709	1.0303	0.697
5a	15 mph	Automated	5.394	-0.551	1.369	0.977
5b	15 mph	Automated	5.197	-0.551	2.297	1.217
5c	15 mph	Automated	5.276	0.0	1.875	0.987

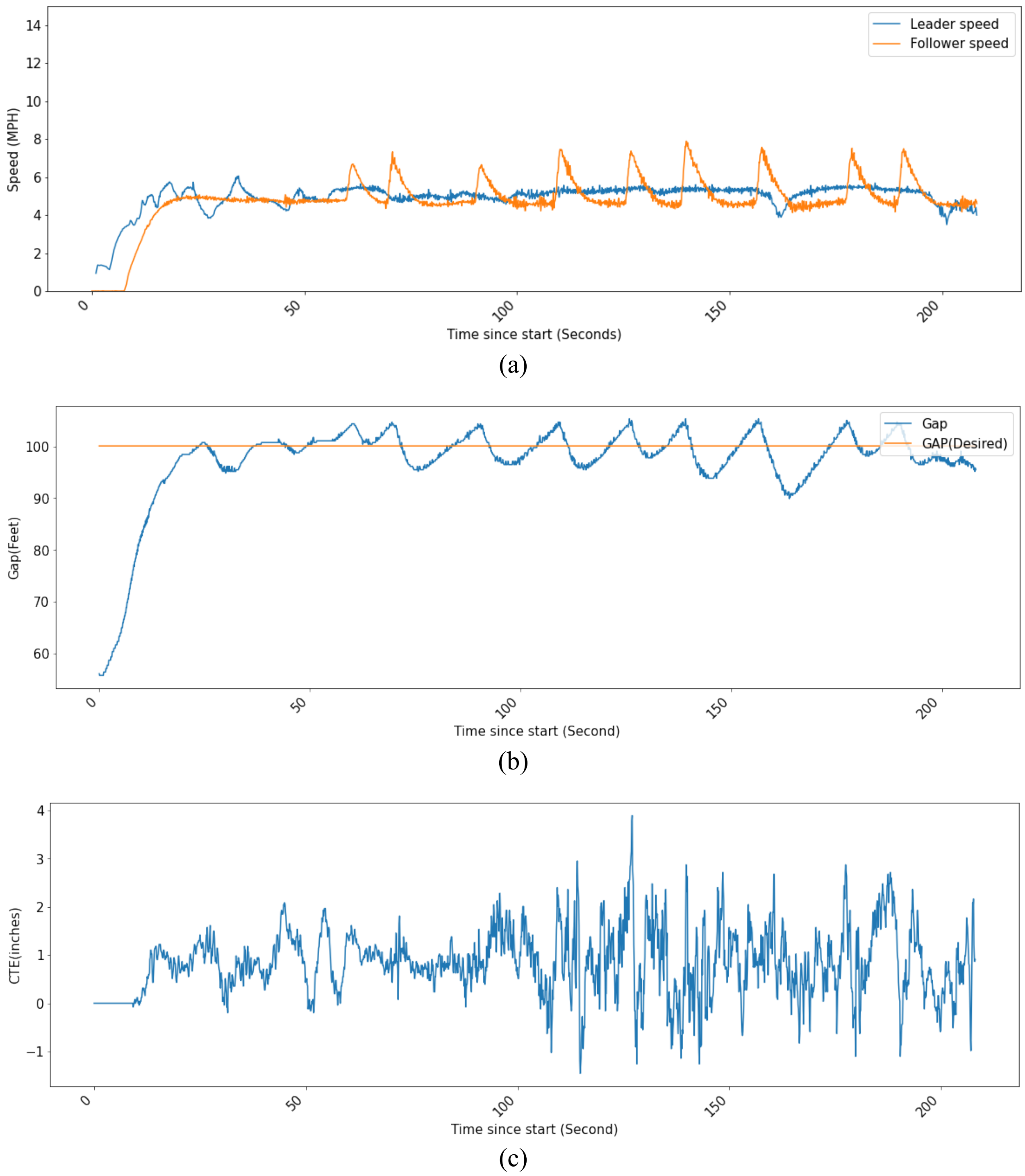
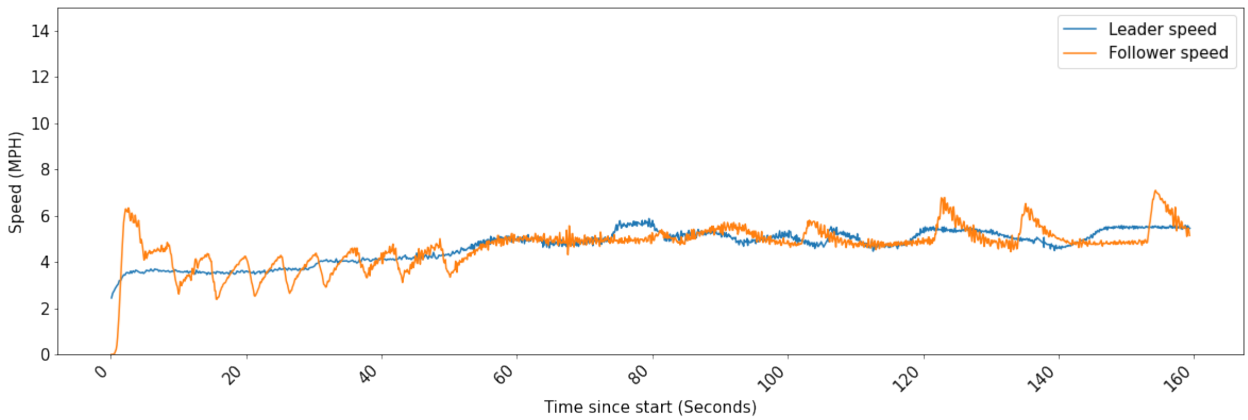


Figure B.3 Test case 7, Run 1a: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.



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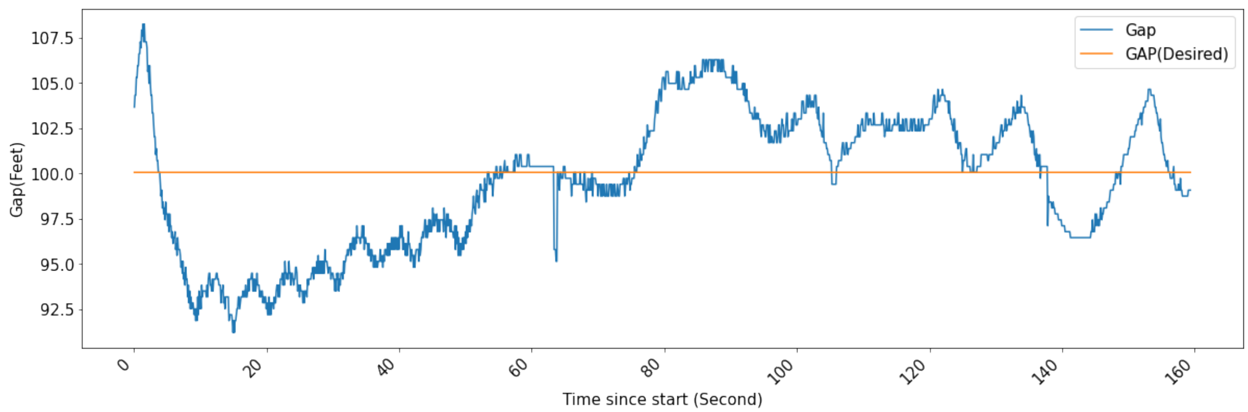

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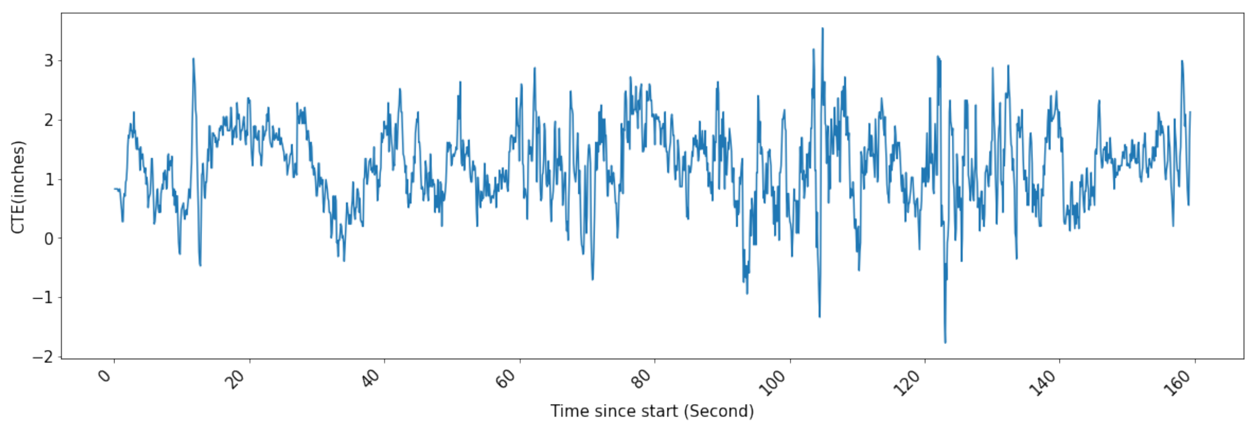

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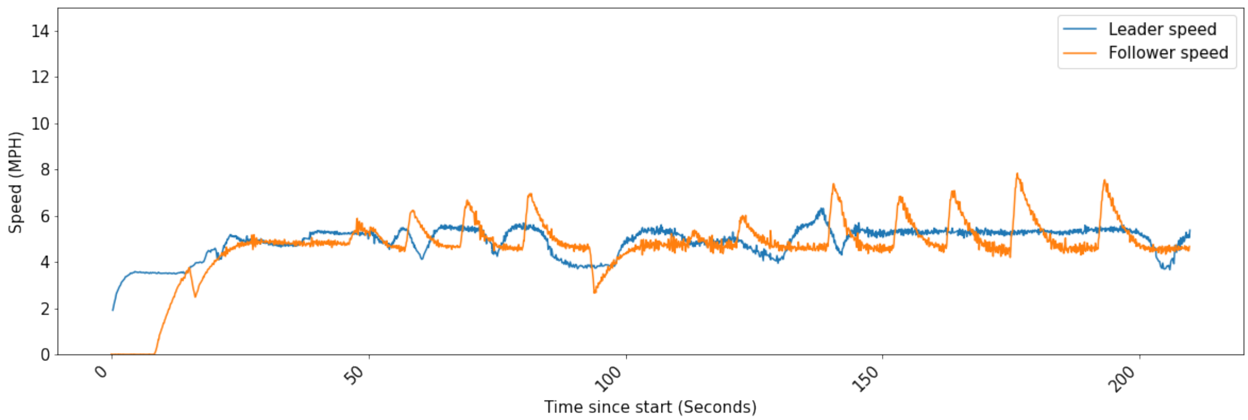
Figure B.4 Test case 7, Run 1b: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.



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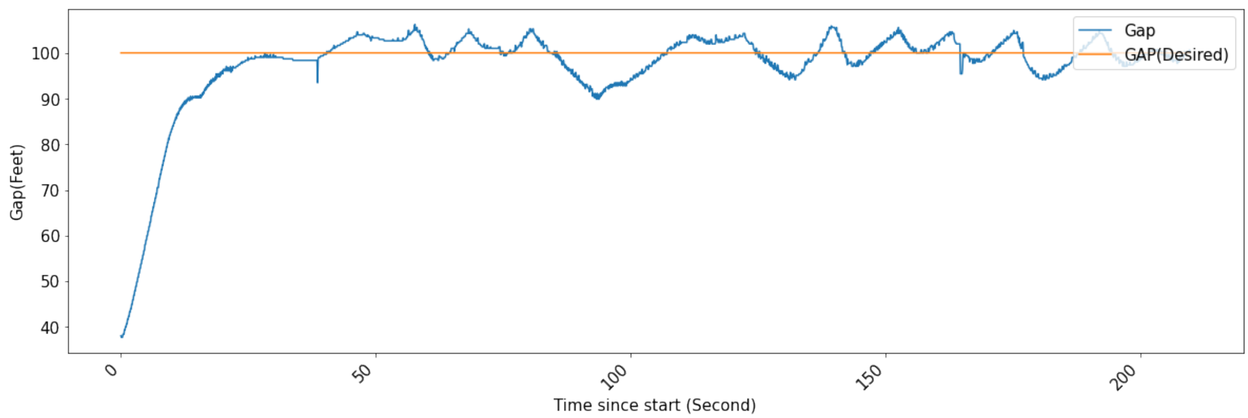

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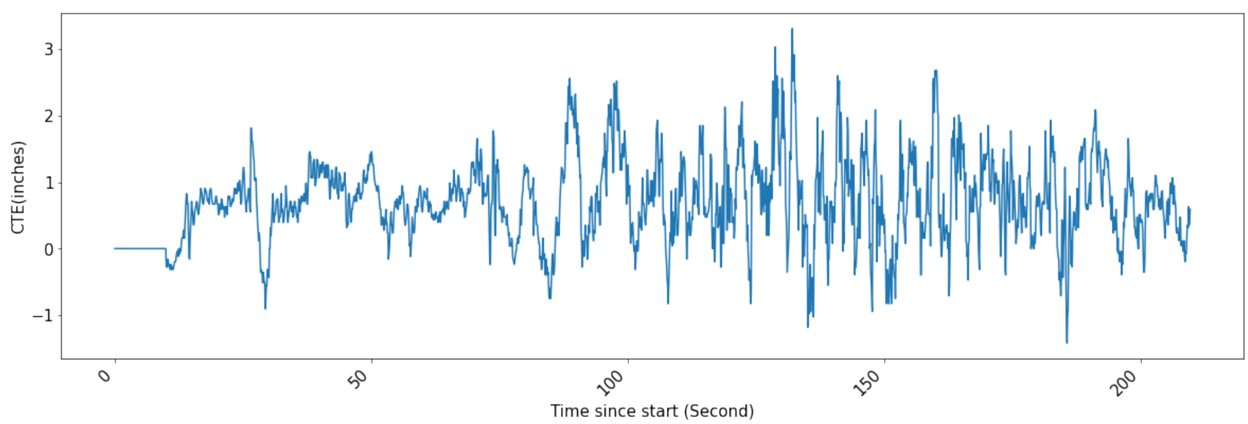

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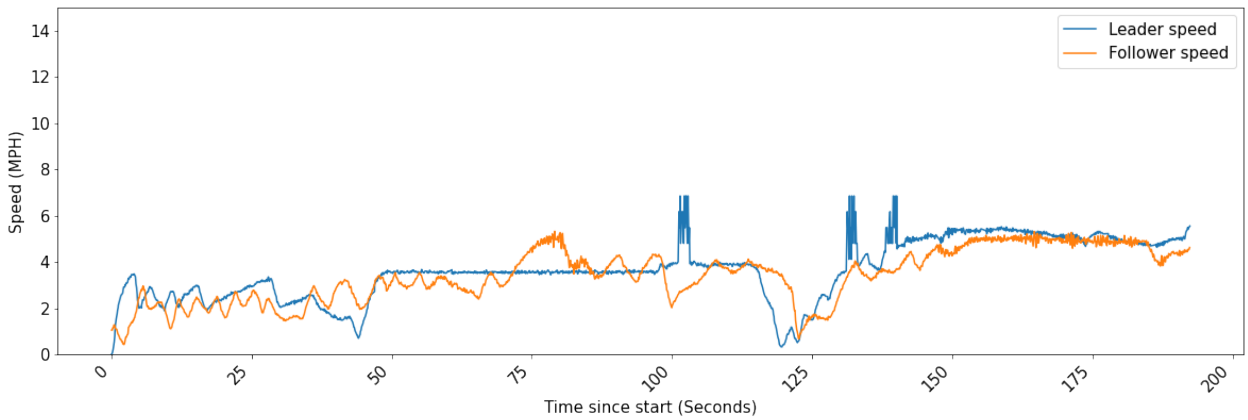
Figure B.5 Test case 7, Run 1c: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.



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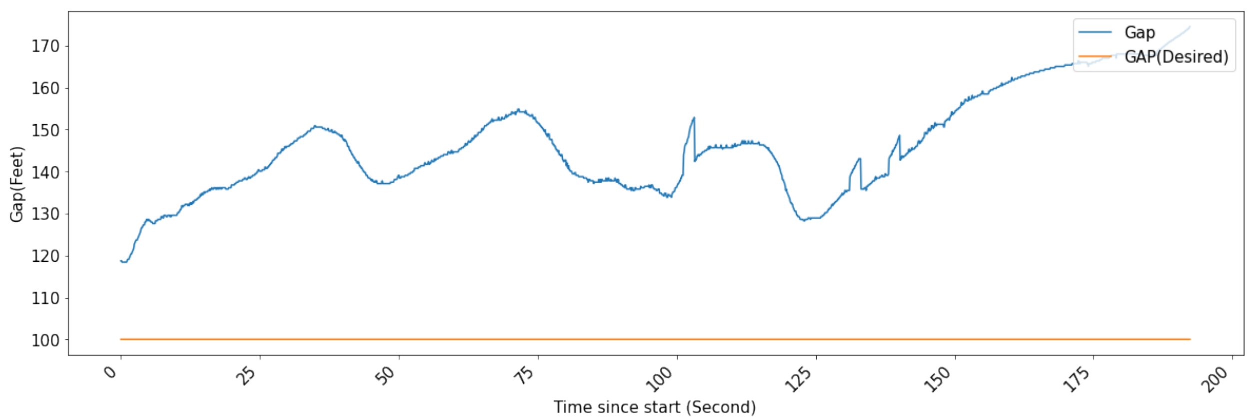

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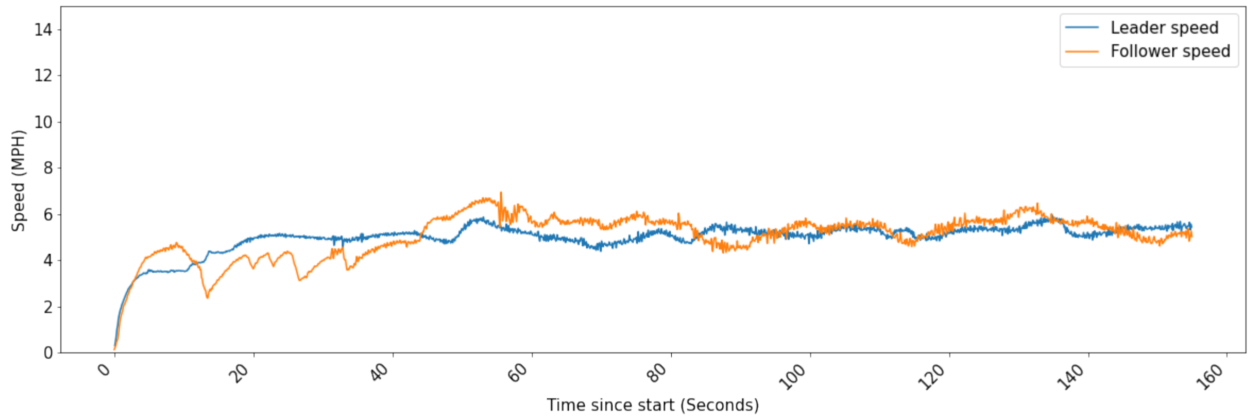
Figure B.6 Test case 7, Run 2a: (a) leader truck speed vs. follower truck speed, and (b) gap vs. desired gap.



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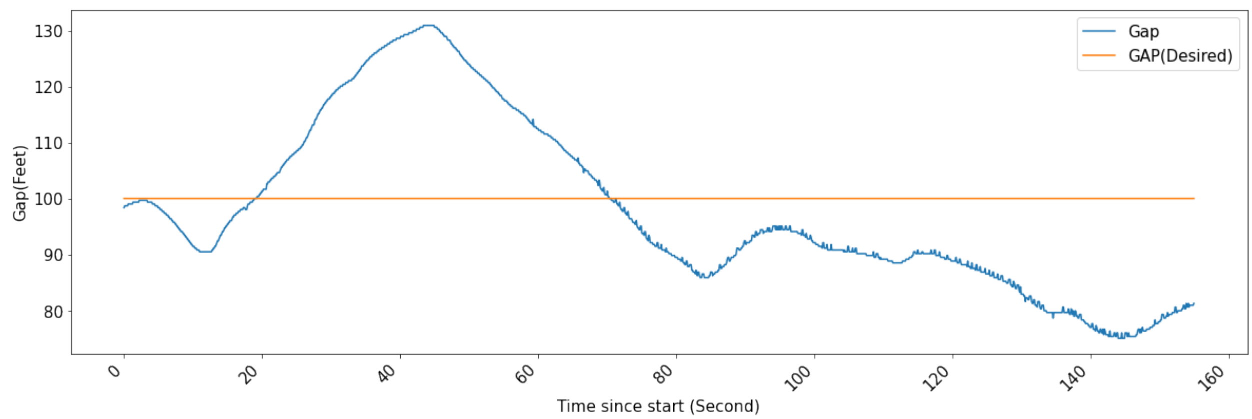

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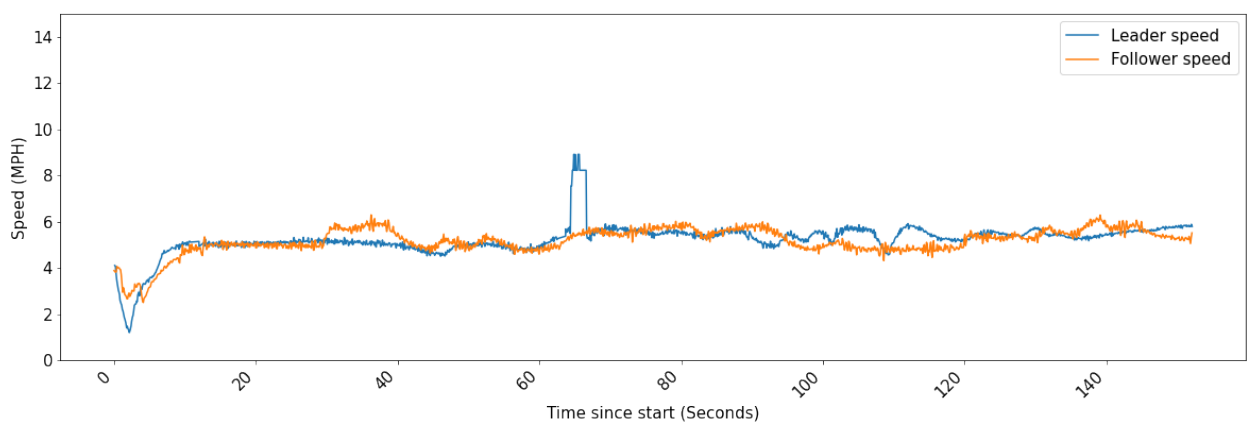
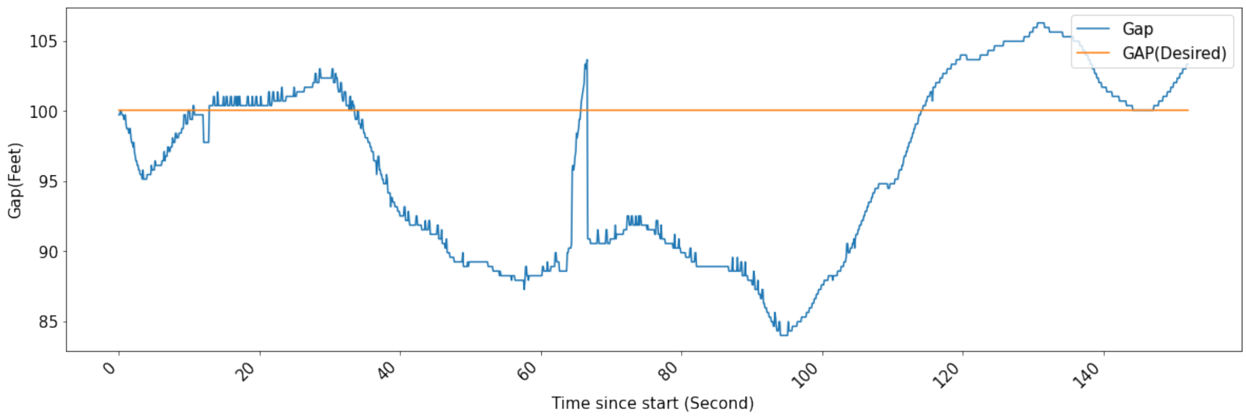
Figure B.7 Test case 7, Run 2b: (a) leader truck speed vs. follower truck speed, and (b) gap vs. desired gap.

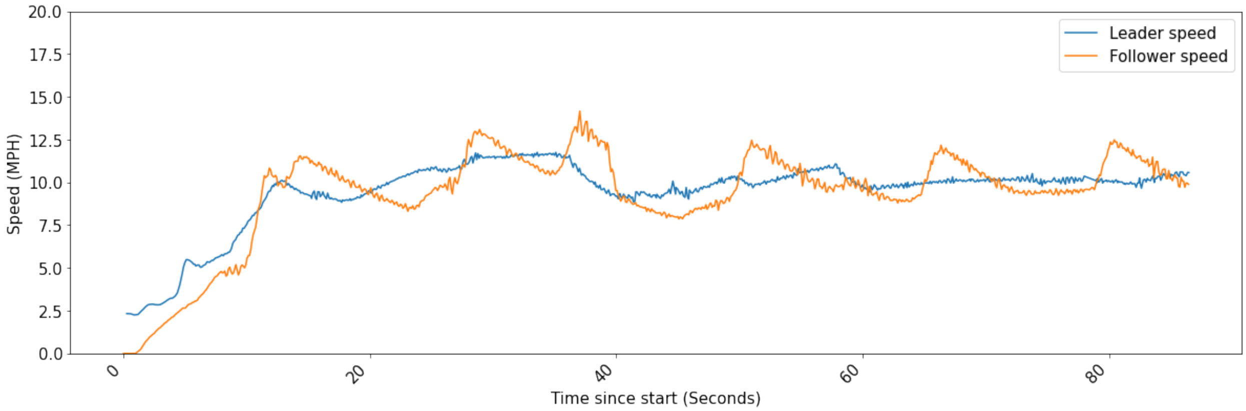


(a)

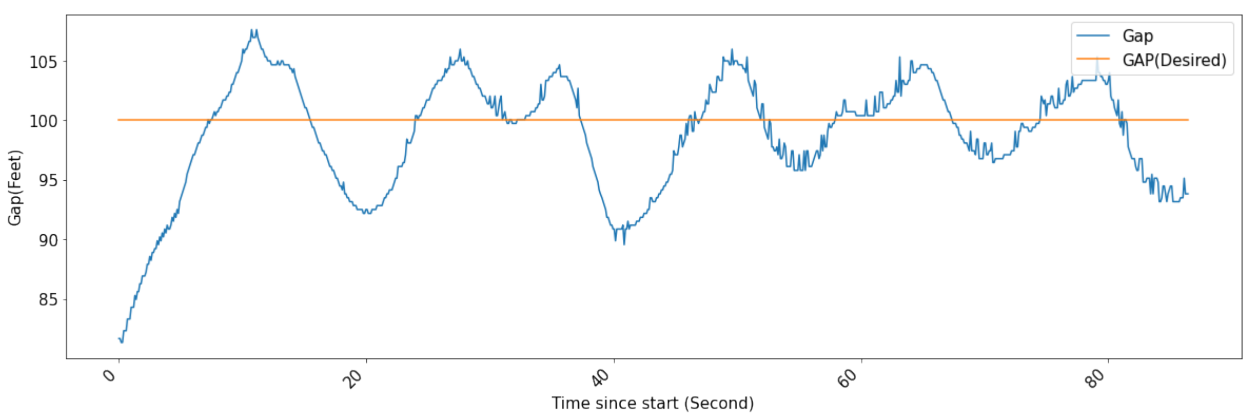


(b)

Figure B.8 Test case 7, Run 2c: (a) leader truck speed vs. follower truck speed, and (b) gap vs. desired gap.



(a)



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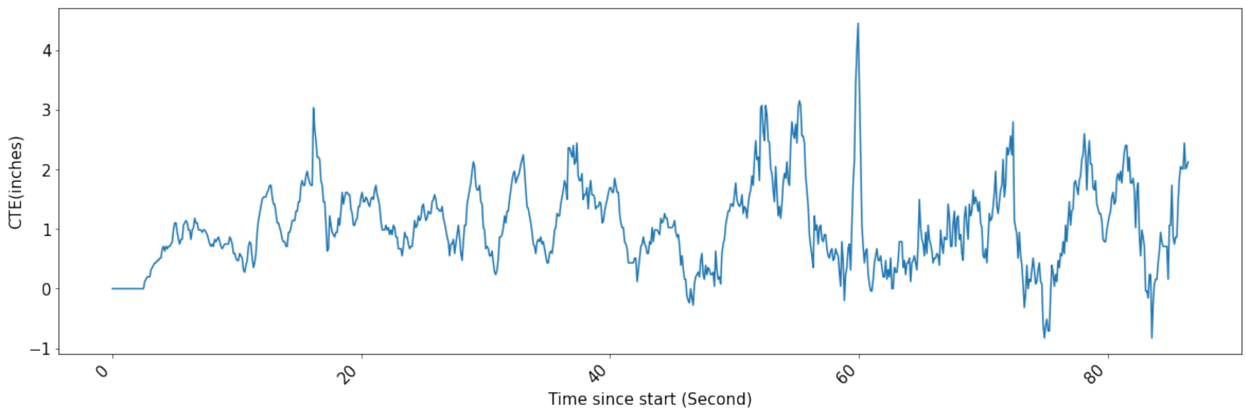
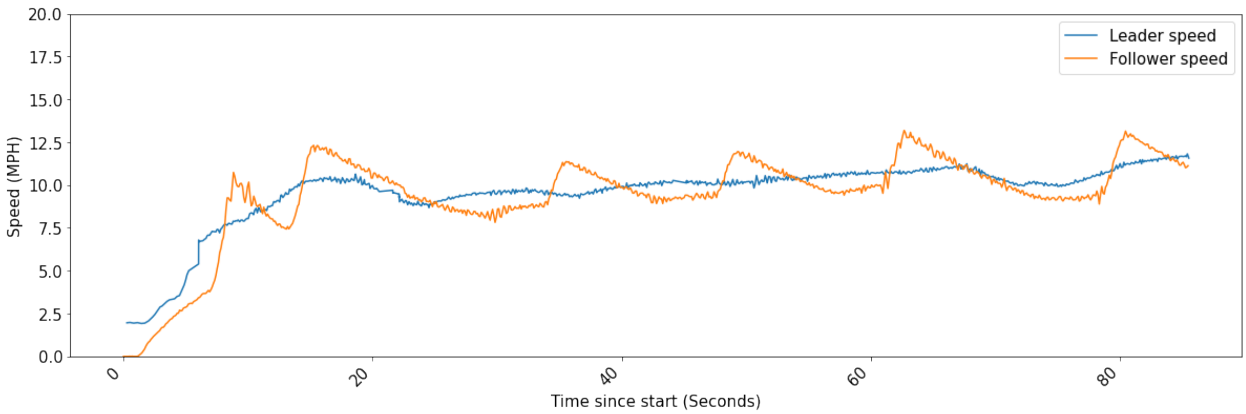


(c)

Figure B.9 Test case 7, Run 3a: (a) leader truck speed vs. follower truck speed, and (b) gap vs. desired gap, (c) CTE.



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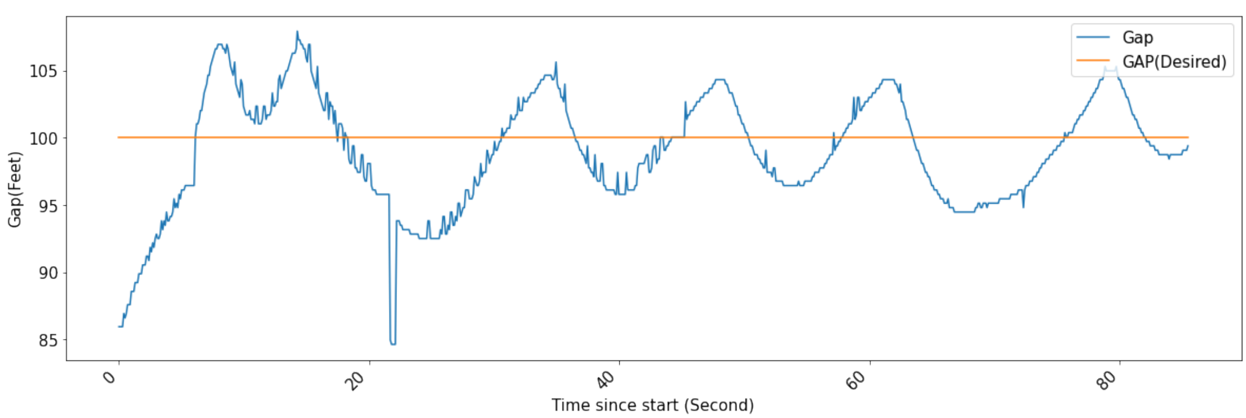

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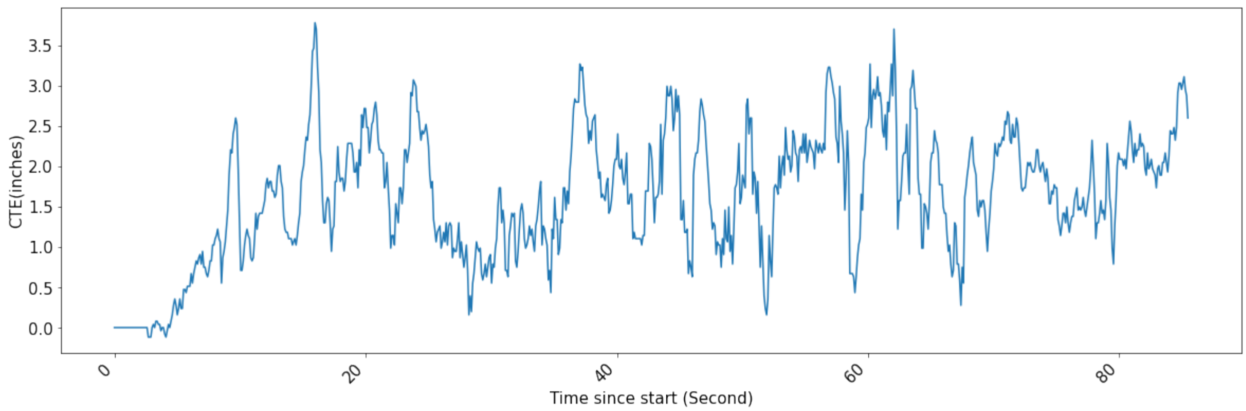
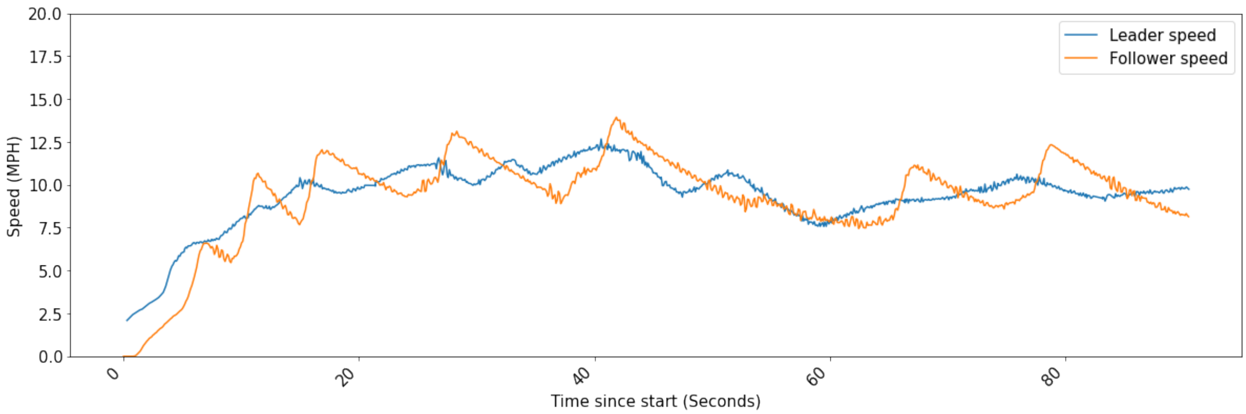


(c)

Figure B.10 Test case 7, Run 3b: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.



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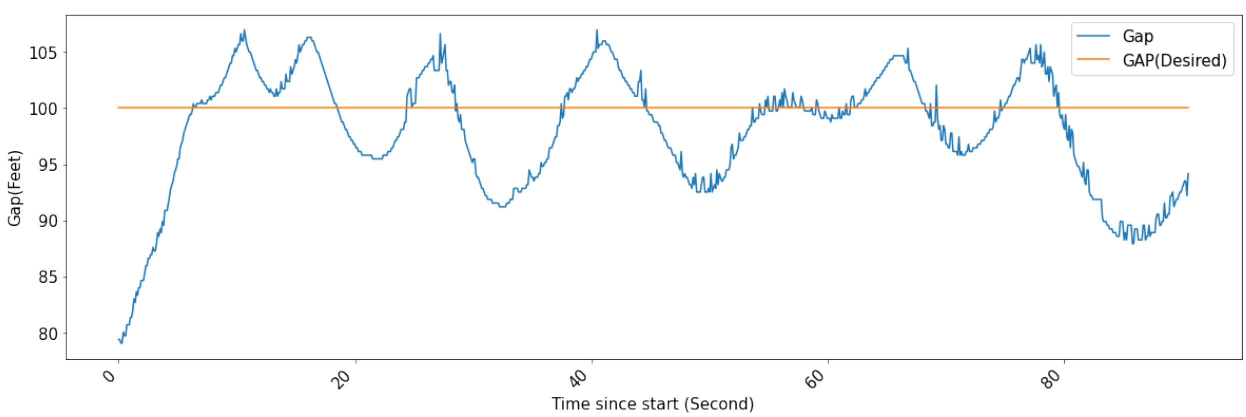

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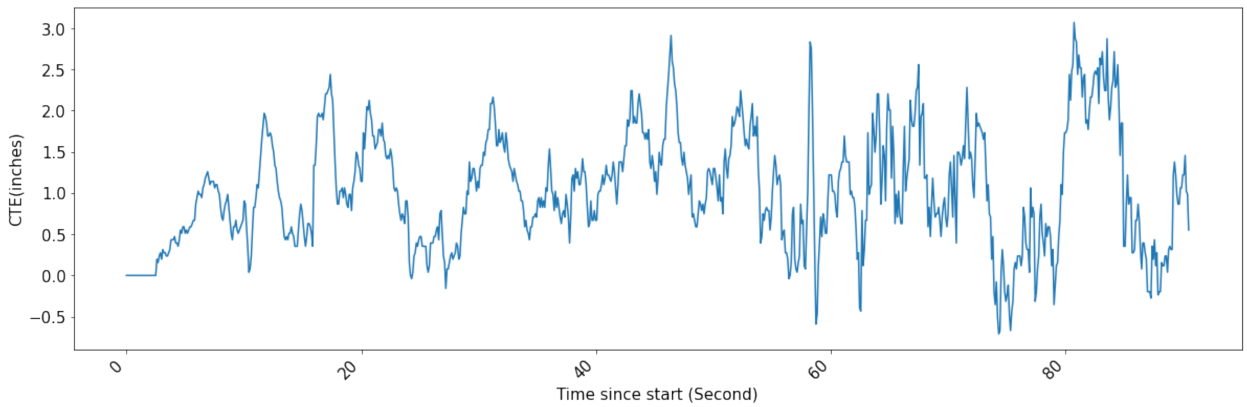
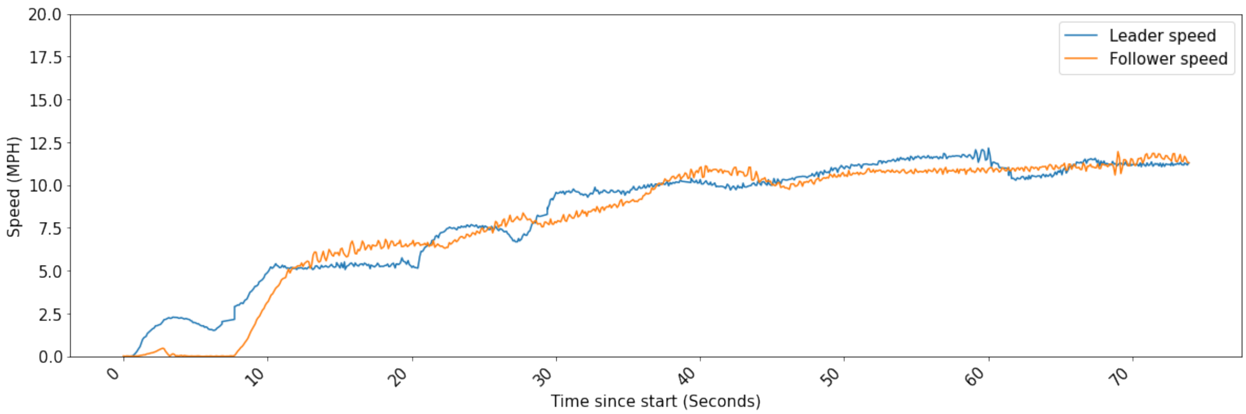


(c)

Figure B.11 Test case 7, Run 3c: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.



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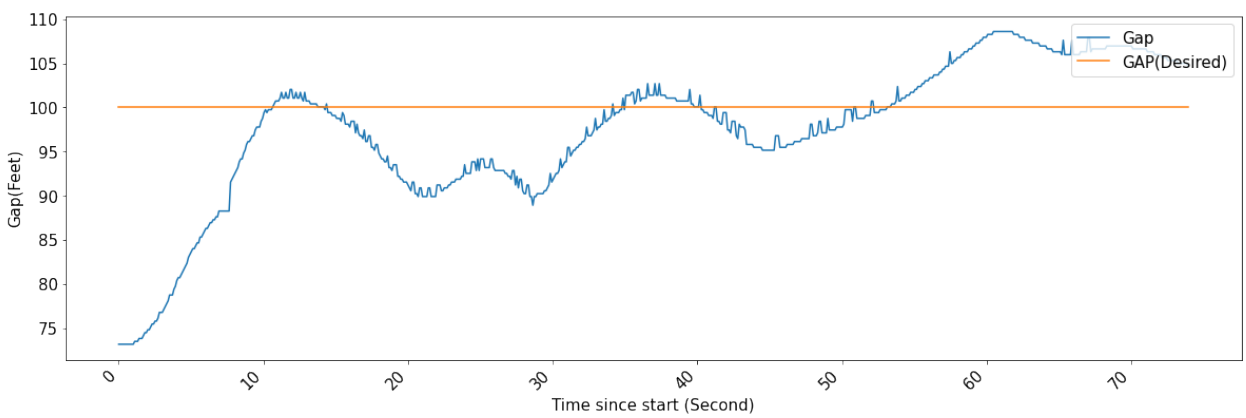
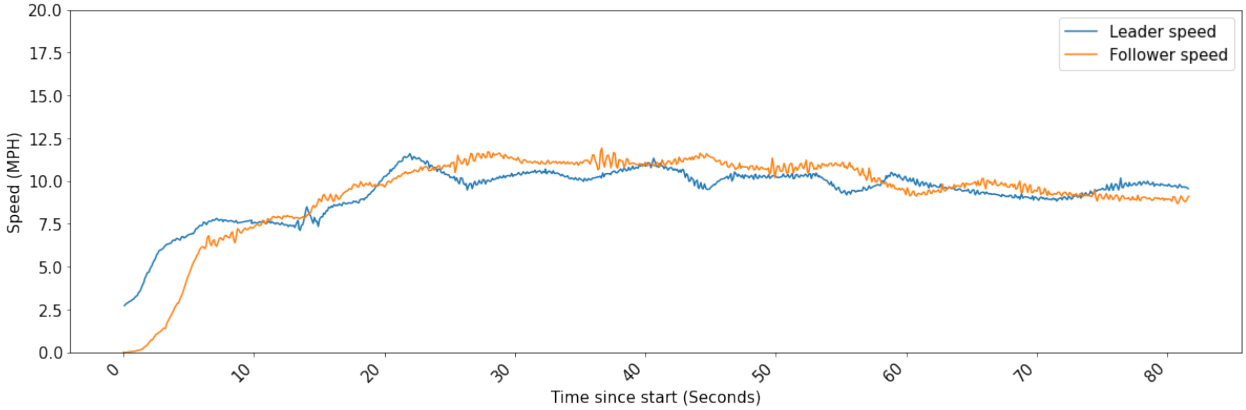
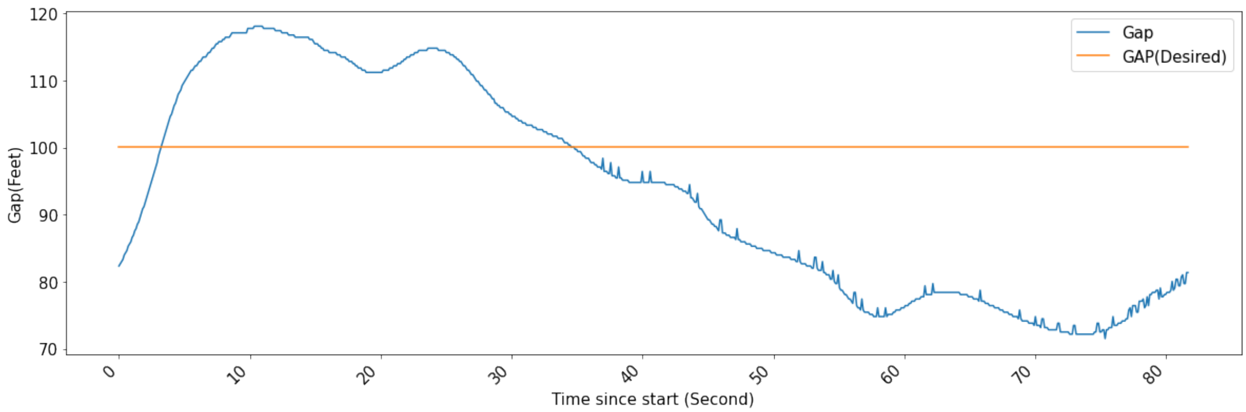


(b)

Figure B.12 Test case 7, Run 4a: (a) leader truck speed vs. follower truck speed, and (b) gap vs. desired gap.

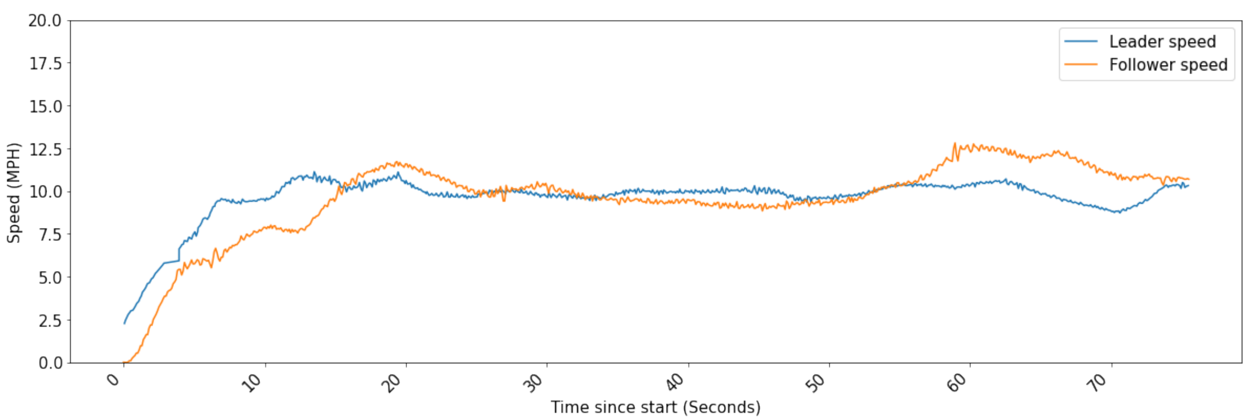


(a)

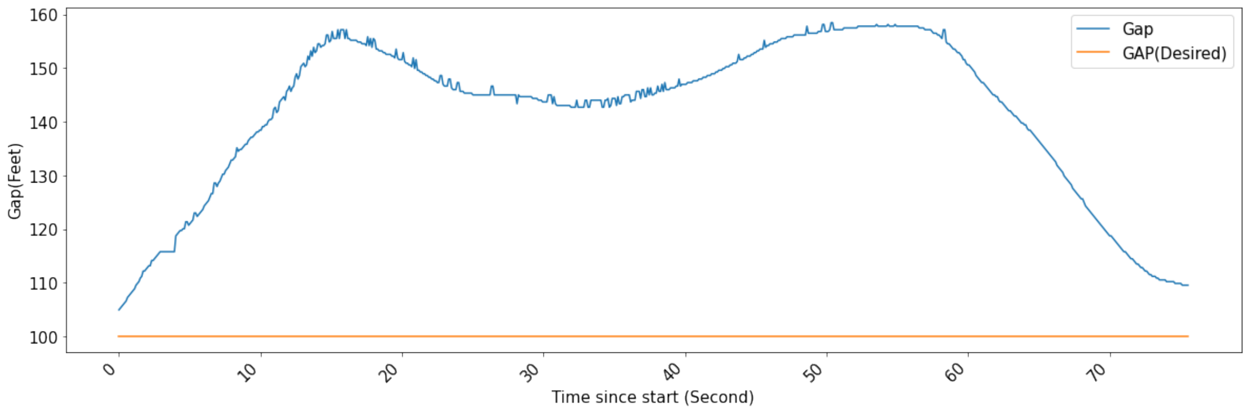


(b)

Figure B.13 Test case 7, Run 4b: (a) leader truck speed vs. follower truck speed, and (b) gap vs. desired gap

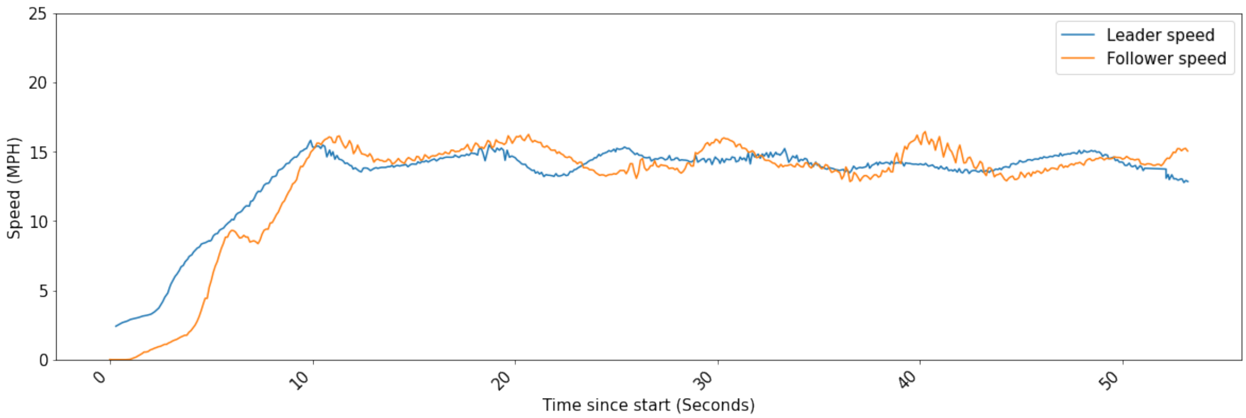


(a)

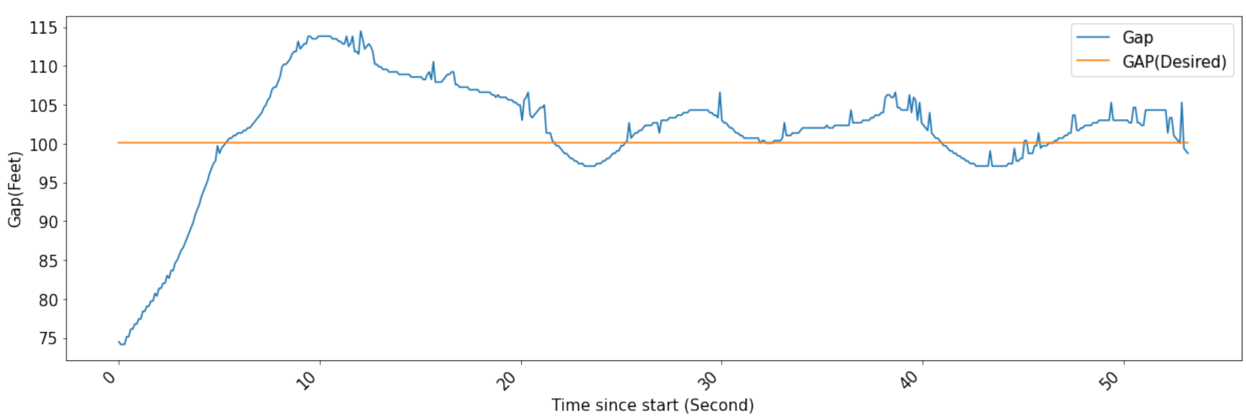


(b)

Figure B.14 Test case 7, Run 4c: (a) leader truck speed vs. follower truck speed, and (b) gap vs. desired gap.



(a)



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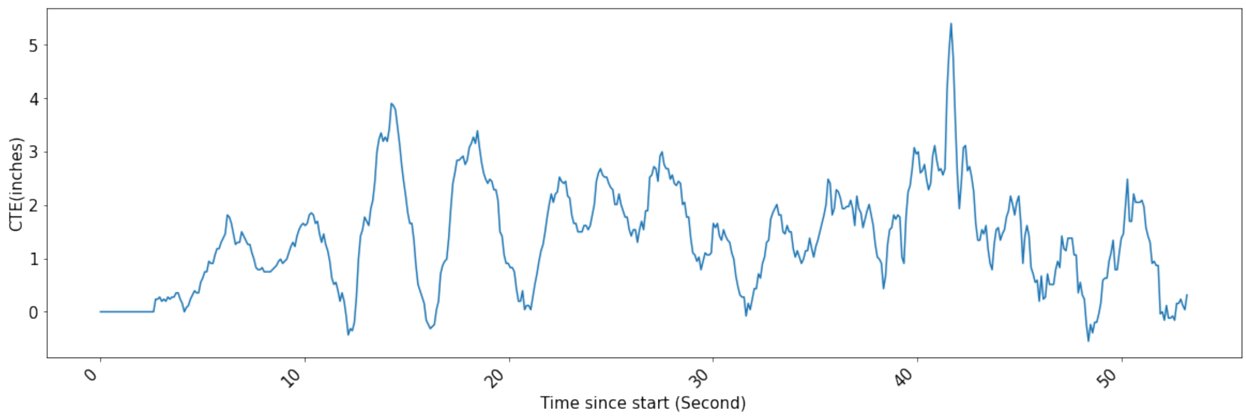
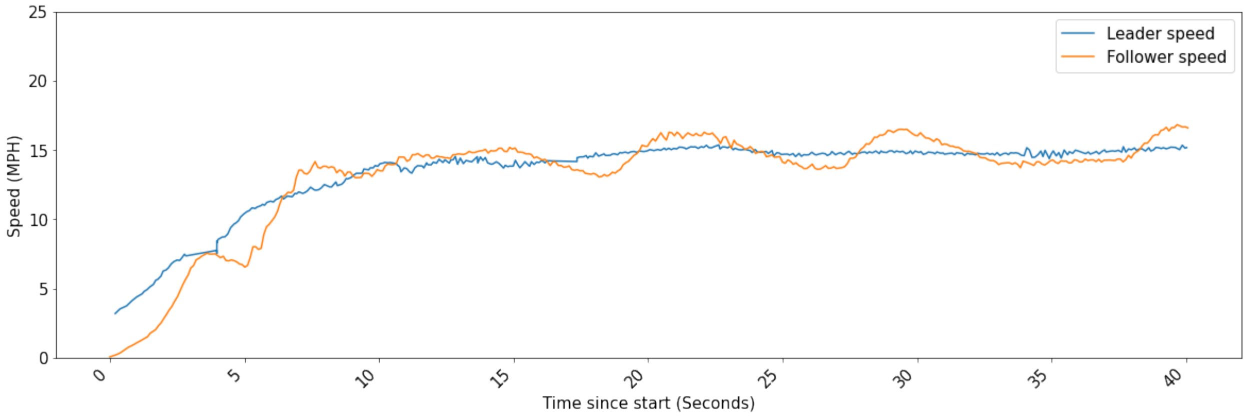
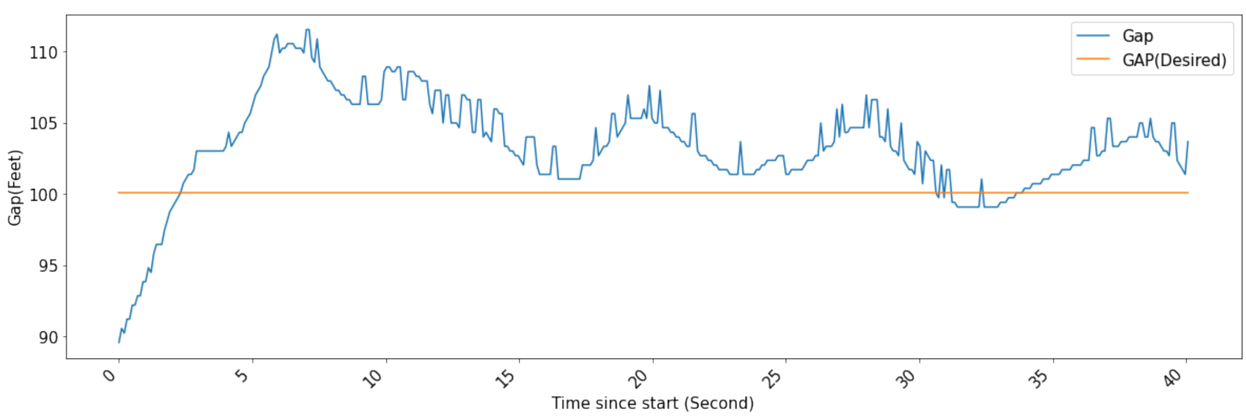


(c)

Figure B.15 Test case 7, Run 5a: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.



(a)



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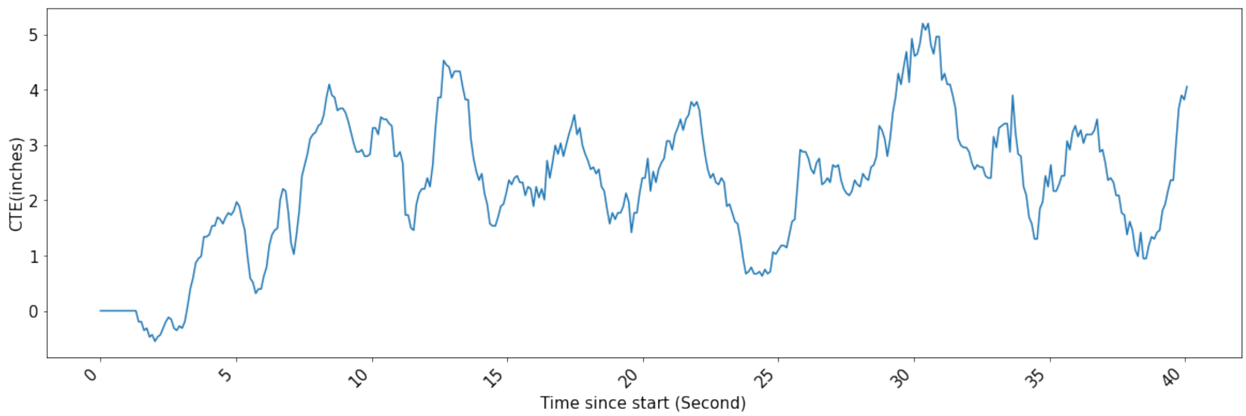
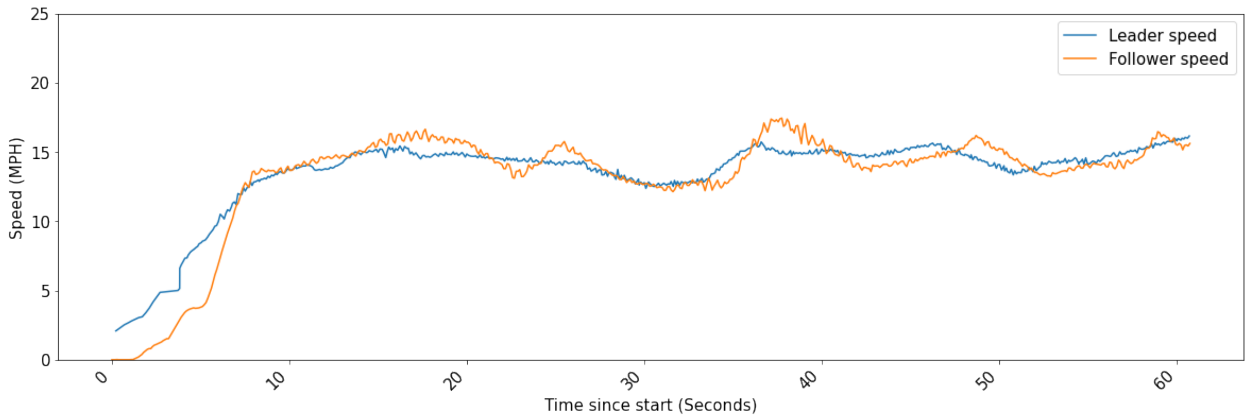
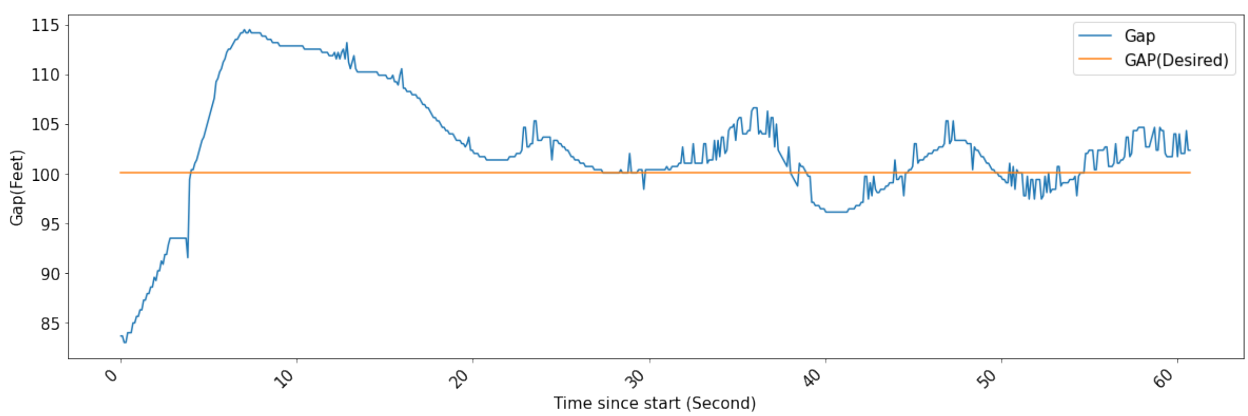


(c)

Figure B.16 Test case 7, Run 5b: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.



(a)



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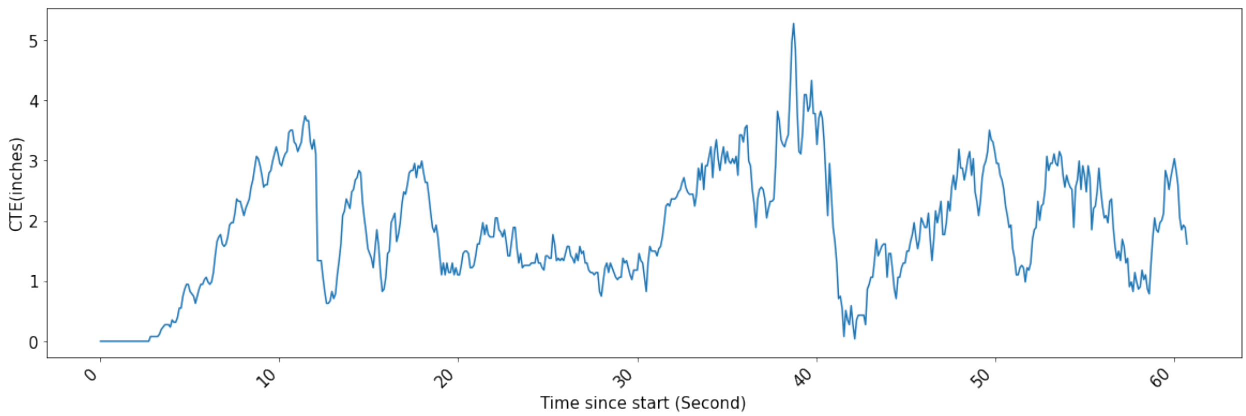
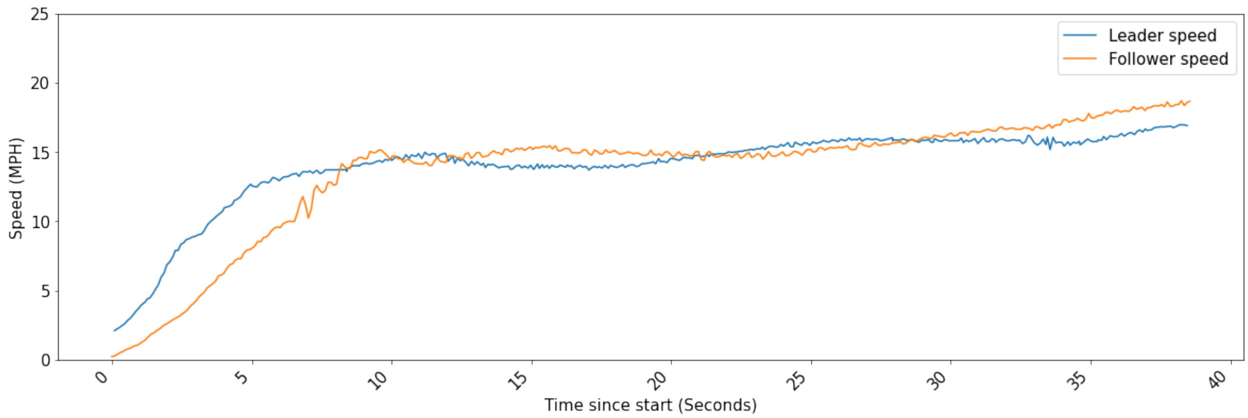
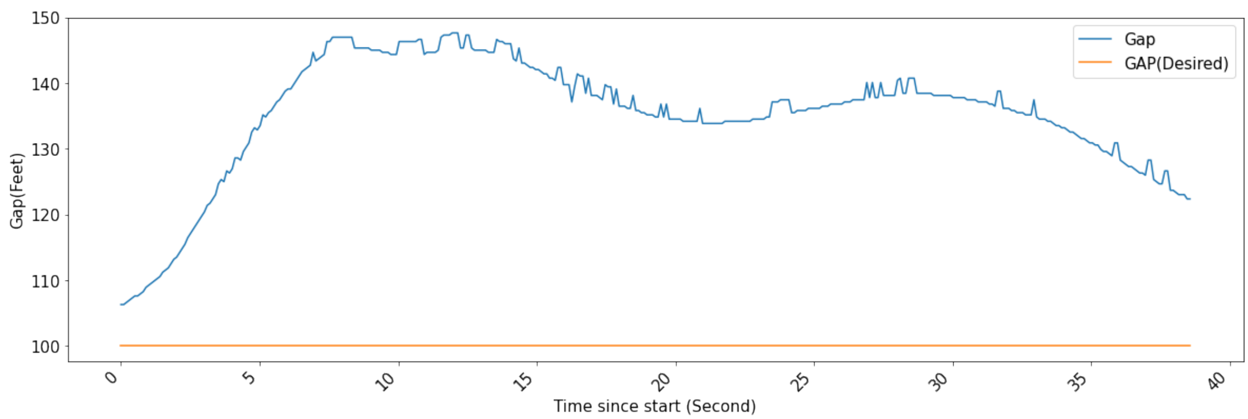


(c)

Figure B.17 Test case 7, Run 5c: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.

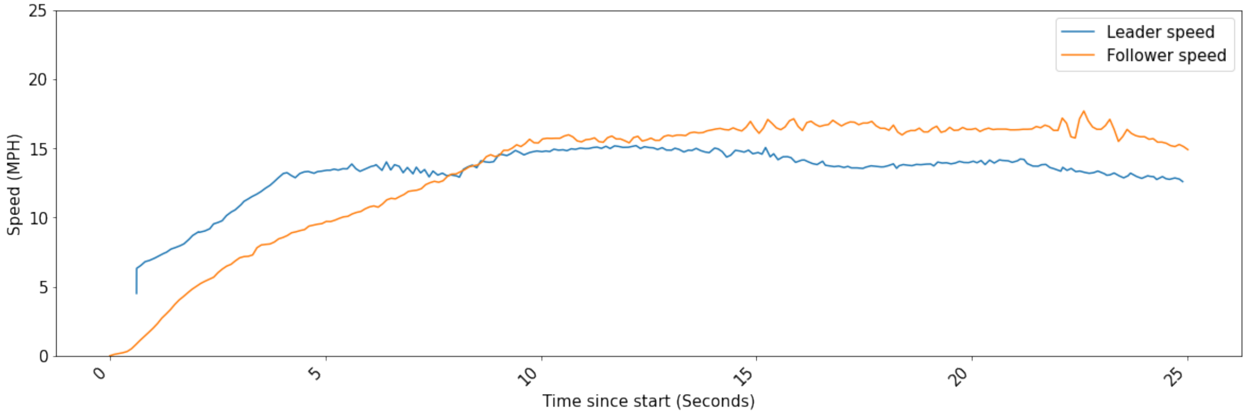


(a)

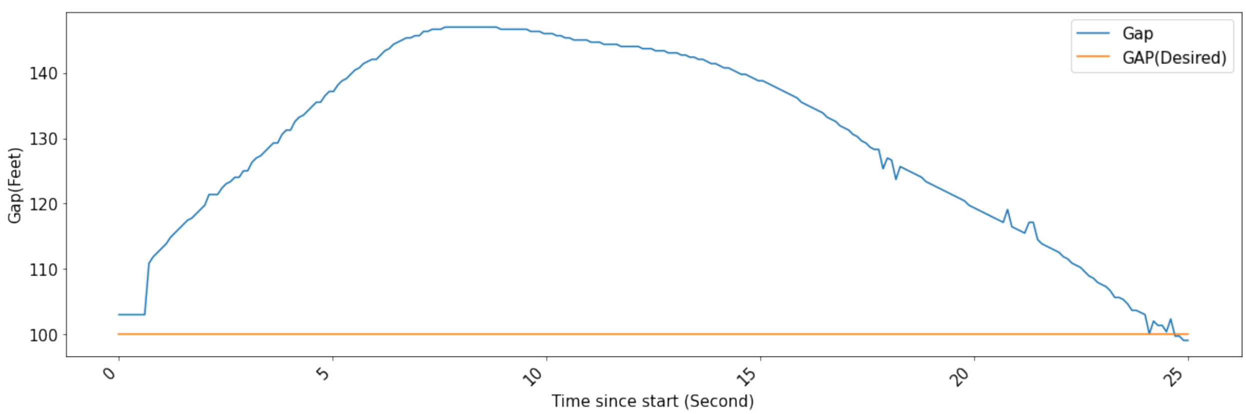


(b)

Figure B.18 Test case 7, Run 6a: (a) leader truck speed vs. follower truck speed, and (b) gap vs. desired gap.

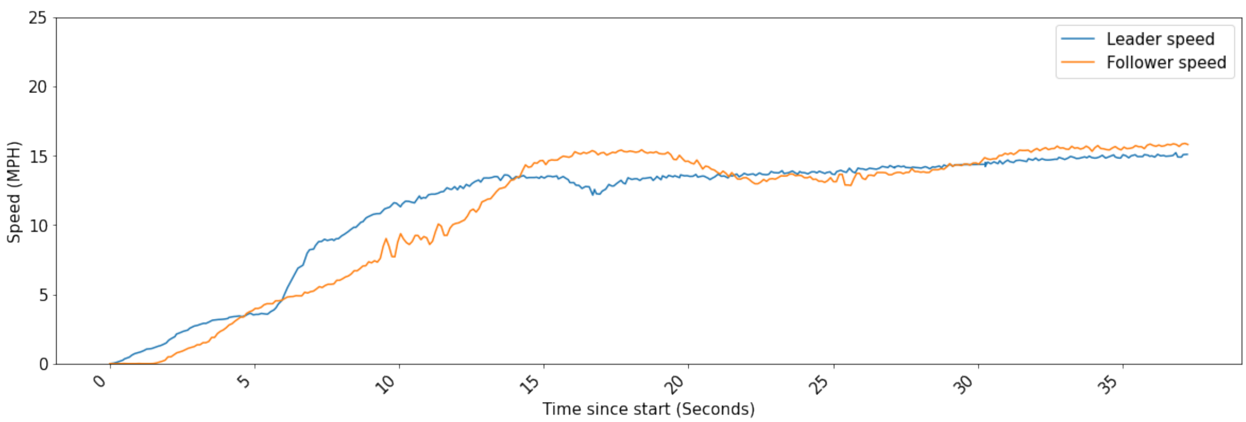


(a)

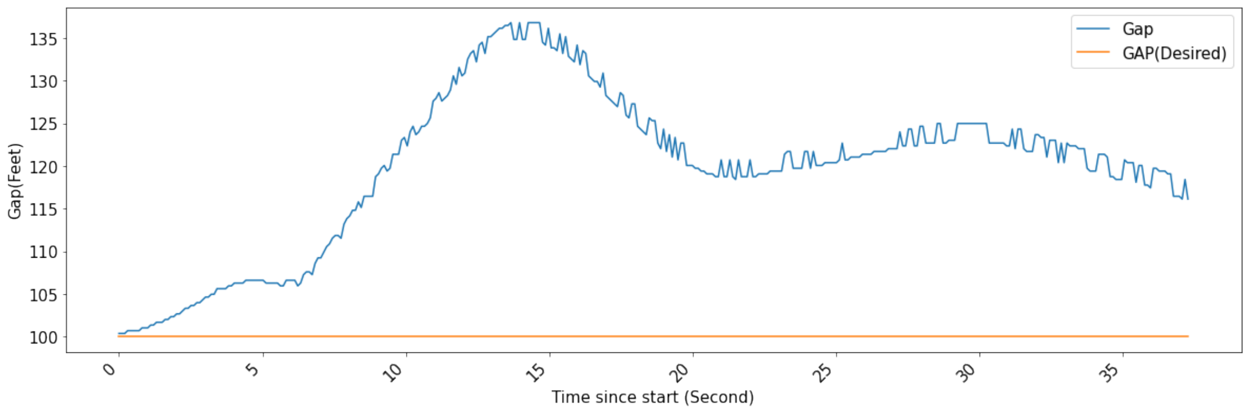


(b)

Figure B.19 Test case 7, Run 6b: (a) leader truck speed vs. follower truck speed, and (b) gap vs. desired gap.



(a)



(b)

Figure B.20 Test case 7, Run 6c: (a) leader truck speed vs. follower truck speed, and (b) gap vs. desired gap.

Test Case 8: Following Accuracy on Slalom Course

Table B.18 Test Procedure-Test Case 8

Pre-procedure	• Placed 5 cones in a straight line with 100 feet in-between distance.
Operation procedure	• Activated the leader truck and ATMA and set the gap to 100 feet and drive on a slalom course at 5 mph. • Drove the ATMA in idle mode by a human driver with 100 feet gap on a slalom course at 5 mph. • Repeated the test at speeds of 10 mph and 15 mph. • Conducted 3 runs for each speed.
Data collection	• Collected ATMA following gap accuracy. • Collected ATMA lateral accuracy.
Expected results	• The ATMA maintains the following gap accuracy. • The ATMA maintains a lateral accuracy of ±6 inches from the leader's path based on the ATMA log file. • The ATMA system has better following gap accuracy and lateral accuracy when operated autonomously than driven by a human driver.
Total number of runs	9 runs (Each run has two subtasks.)
Supporting equipment	Walkie-talkie, Traffic cones

Figure B.21 shows the layout of the slalom course test.

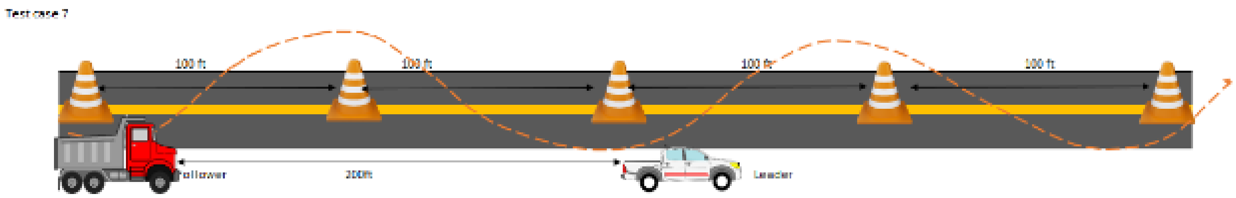


Figure B.21 The layout of slalom test setup (Agarwal et al. 2021).

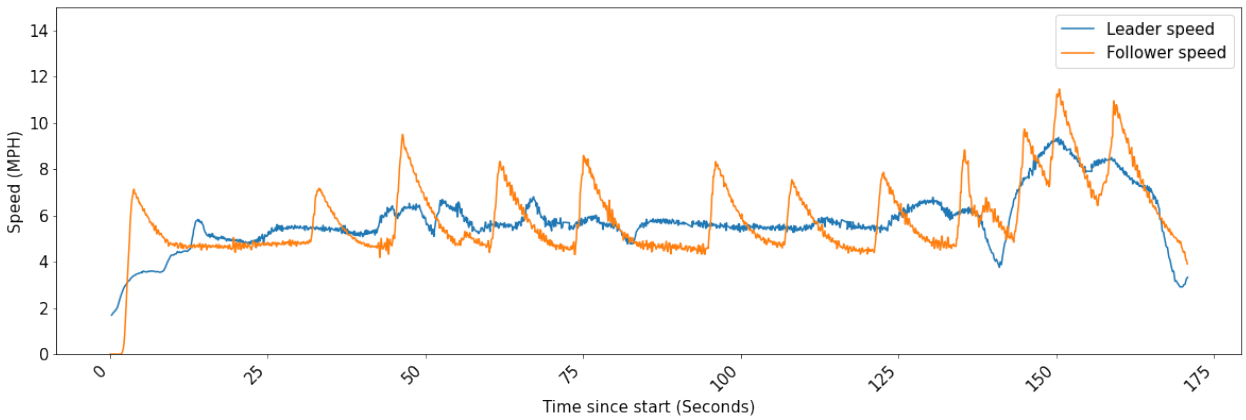
An A-stop happened during case 1-c, which is not considered in the data analysis. Table B.19 and Table B.20 show the gap difference and CTE for each run. The results show automated model had better performance than the idle mode for 5 mph operations in terms of gap difference. However, the idle mode has better performance than the automated mode for 10 mph and 15 mph operations. Based on the filed observations, the follower truck slowed down to pass each traffic cone. Therefore, it is hard for the follower truck to make the commanded gap when operated at high speeds. Table B.20 shows the CTE. The max CTE for all runs is larger than 6 inches which means the ATMA did not meet the design requirement. Figure B.22 to Figure B.38 show leader truck speed vs. follower truck speed, gap vs. the desired gap, and CTE for each run.

Table B.19 Gap difference for each run: Case 8

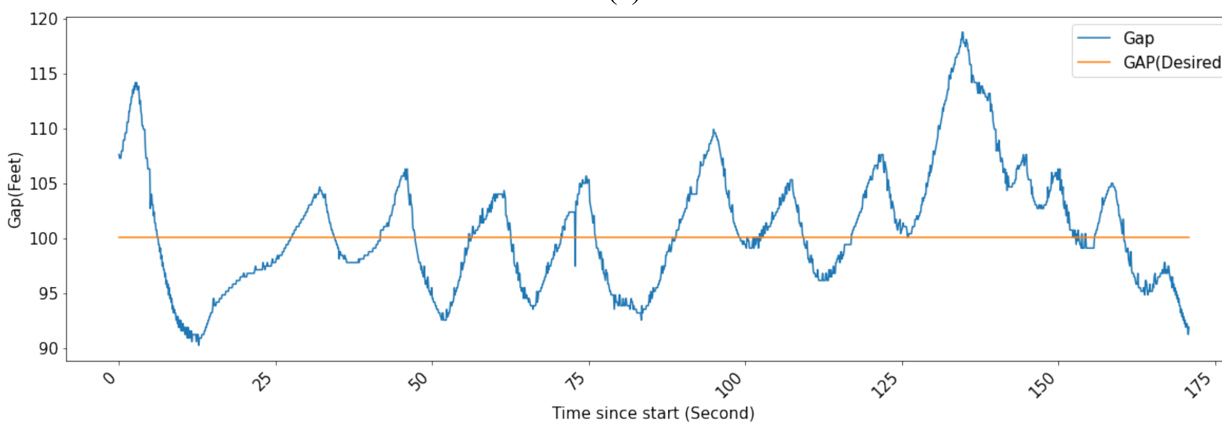
Runs	Test Speed	Mode	Max (feet)	Min (feet)	Mean (feet)	Std. (feet)
1a	5 mph	Automated	18.701	-9.843	0.758	5.522
1b	5 mph	Automated	8.202	13.451	-3.583	3.279
1c	5 mph	Automated	NA			
2a	5 mph	Idle (human driver)	19.357	-20.669	-4.986	10.872
2b	5 mph	Idle (human driver)	42.979	-78.412	-2.540	21.472
2c	5 mph	Idle (human driver)	19.0289	-25.591	-3.685	8.641
3a	10 mph	Automated	297.572	-20.997	140.245	109.603
3b	10 mph	Automated	205.380	-19.0289	53.736	69.585
3c	10 mph	Automated	185.0393	-6.234	77.953	61.698
4a	10 mph	Idle (human driver)	16.732	-37.730	-12.828	14.789
4b	10 mph	Idle (human driver)	20.997	-33.136	-8.268	15.613
4c	10 mph	Idle (human driver)	54.462	-31.496	6.356	25.743
5a	15 mph	Automated	505.577	-2.297	194.260	176.920
5b	15 mph	Automated	247.0473	-3.609	92.843	95.513
5c	15 mph	Automated	249.672	-11.155	110.735	94.337
6a	15 mph	Idle (human driver)	41.0105	-100.0656	-10.726	40.816
6b	15 mph	Idle (human driver)	43.635	-45.275	-1.00185	23.365
6c	15 mph	Idle (human driver)	71.522	-92.520	23.563	49.757

Table B.20 CTE for each run: Case 8

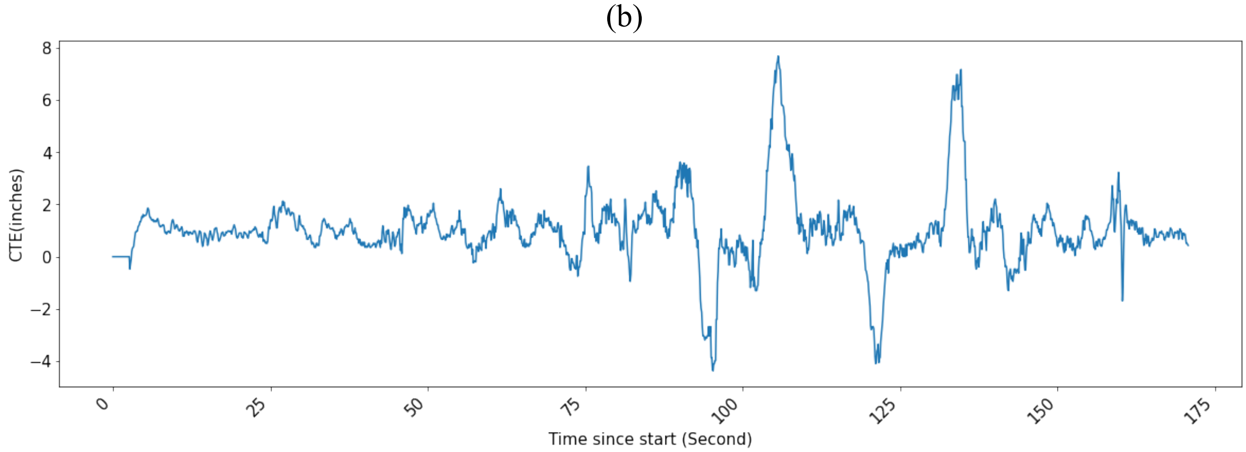
Runs	Test Speed	Mode	CTE (Inches)			
			Max	Min	Average	Std.
1a	5 mph	Automated	7.677	-4.370	1.000408	1.369
1b	5 mph	Automated	7.283	-8.0315	1.358	2.0551
1c	5 mph	Automated	NA			
3a	10 mph	Automated	8.898	-4.764	0.799	2.177
3b	10 mph	Automated	6.0630	-3.858	0.342	1.329
3c	10 mph	Automated	7.559	-3.622	0.889	1.862
5a	15 mph	Automated	11.142	-7.638	0.521	3.801
5b	15 mph	Automated	10.472	-9.449	0.282	2.770
5c	15 mph	Automated	10.433	-7.480	0.347	3.602



(a)



(b)



(c)

Figure B.22 Test case 8, Run 1a: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.

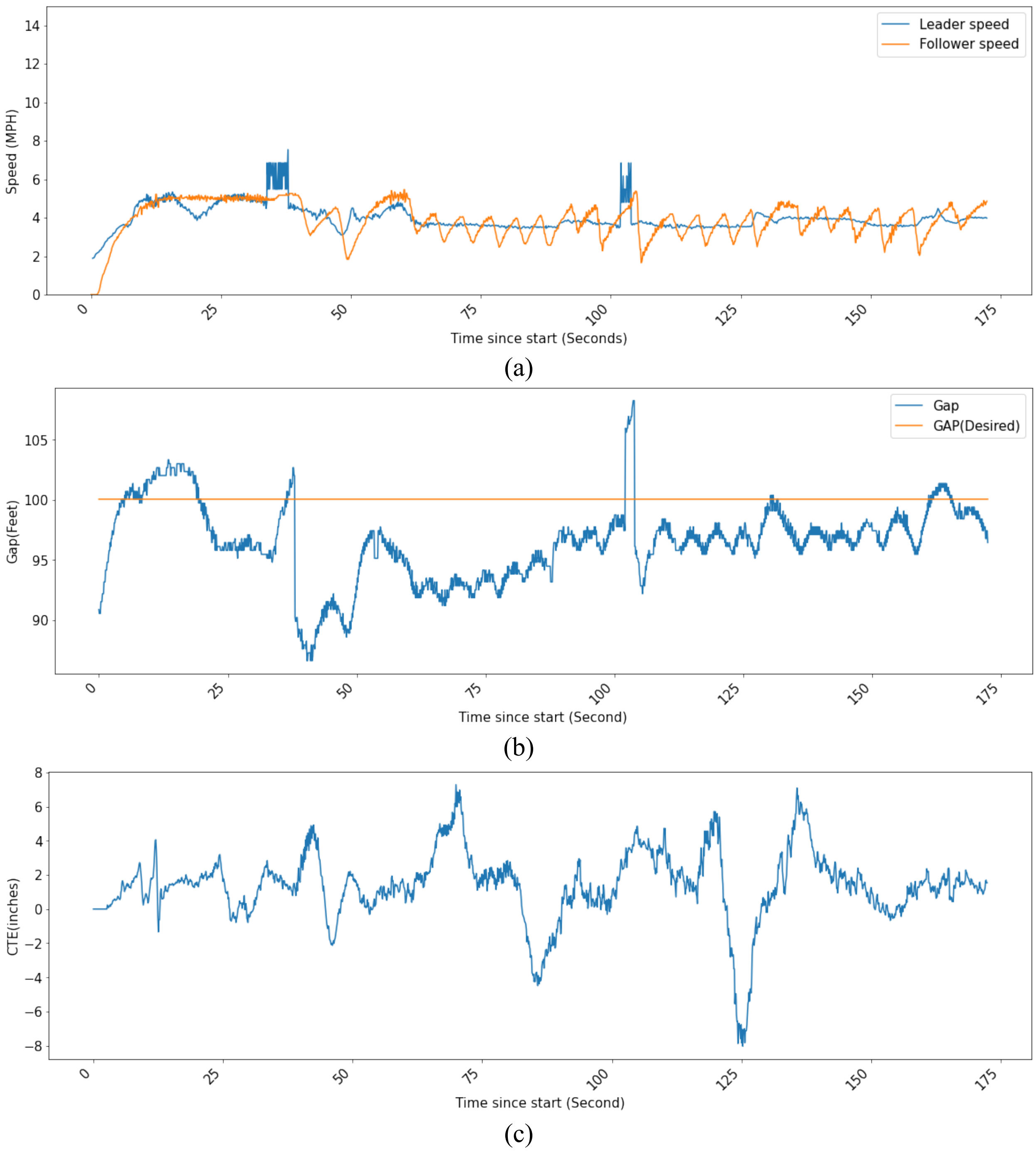
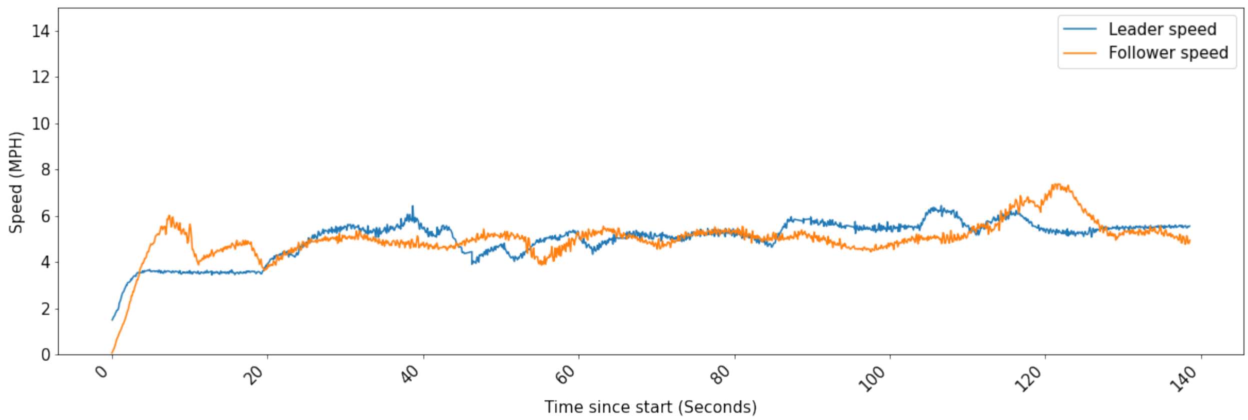


Figure B.23 Test case 8, Run 1b: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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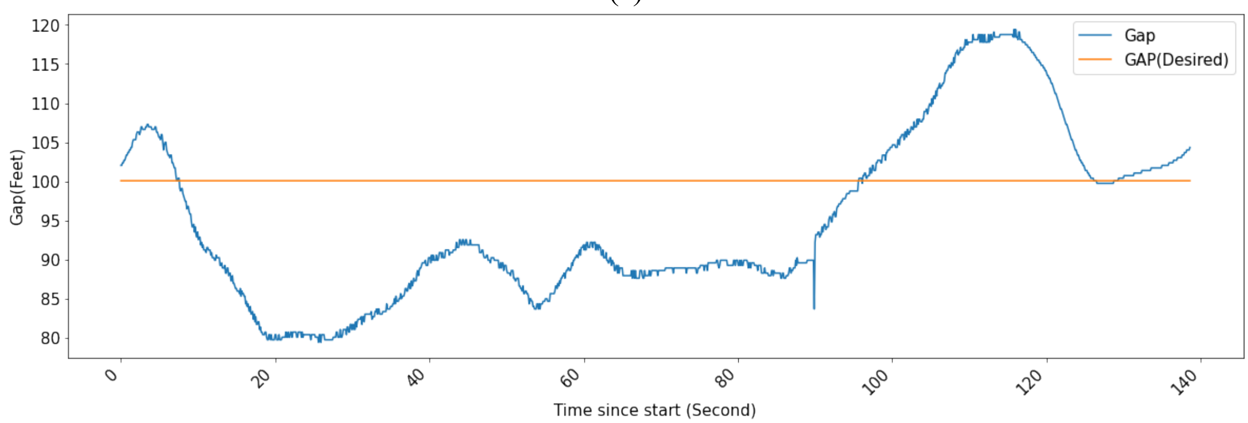
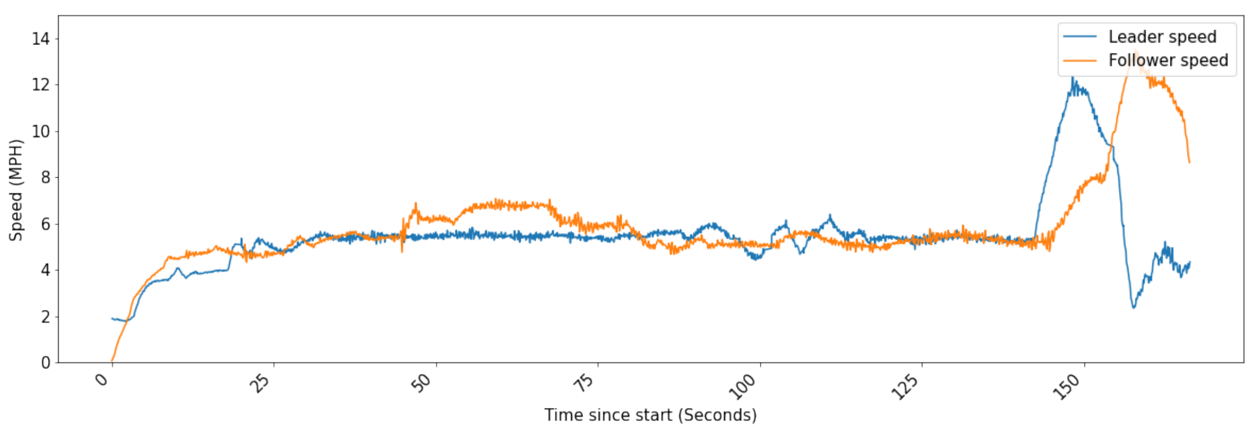
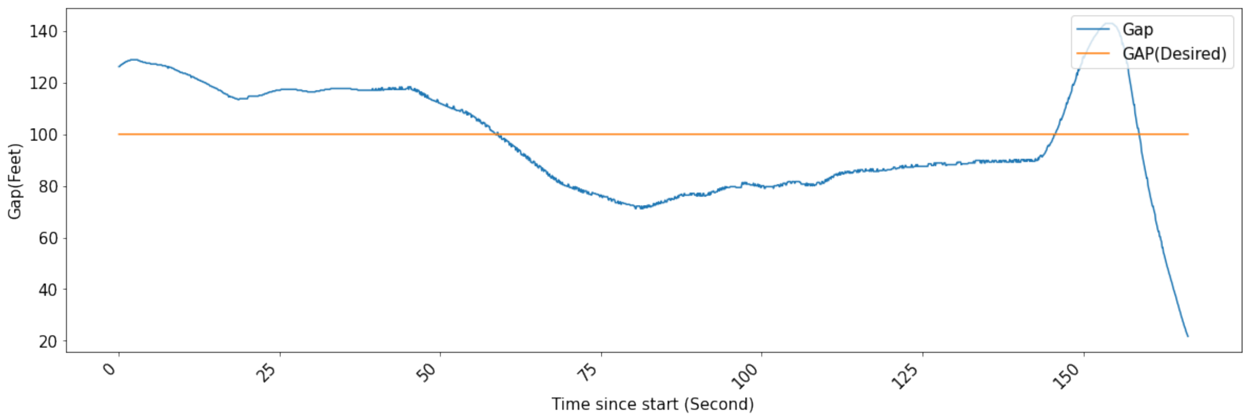


(b)

Figure B.24 Test case 8, Run 2a: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap.

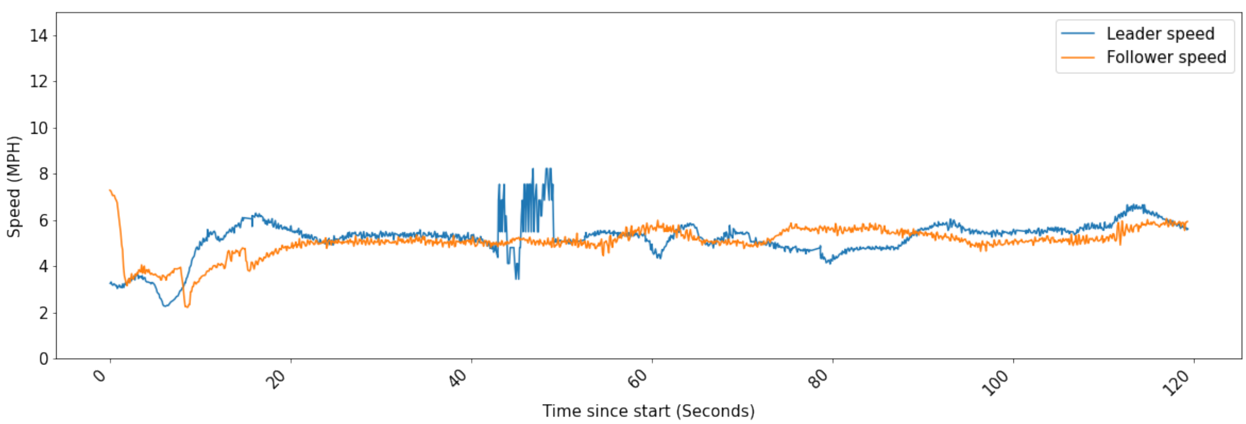


(a)



(b)

Figure B.25 Test case 8, Run 2b: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap.



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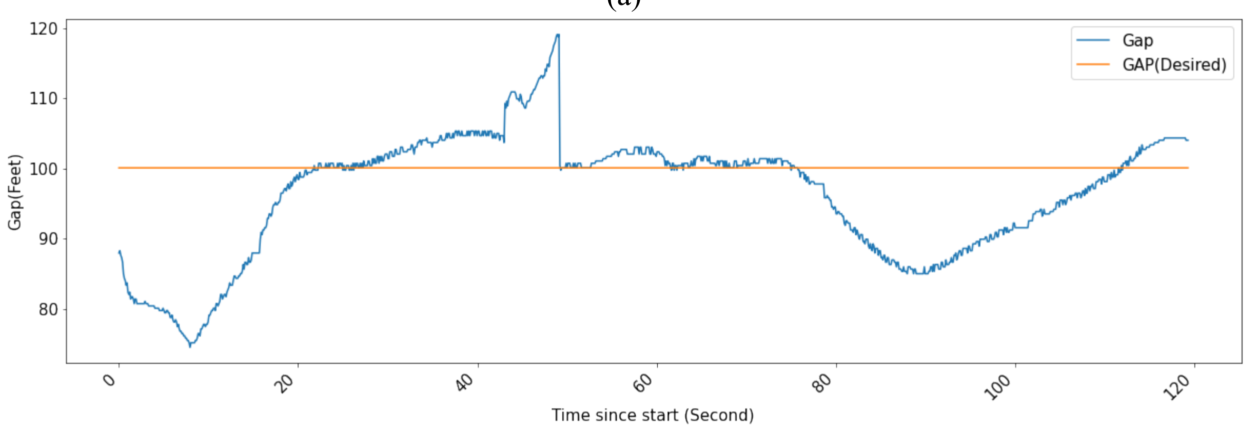


(b)

Figure B.26 Test case 8, Run 2c: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap.

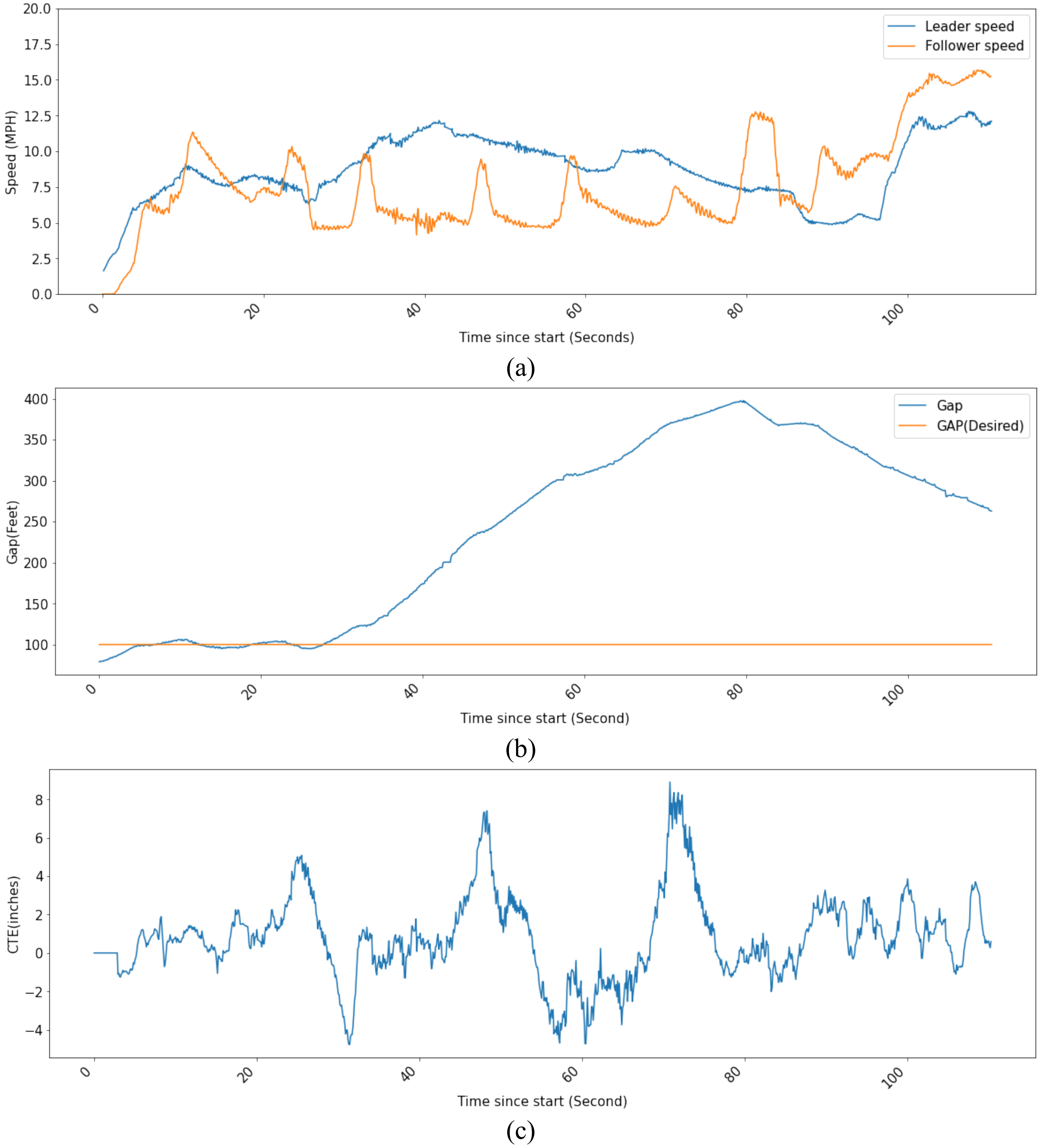
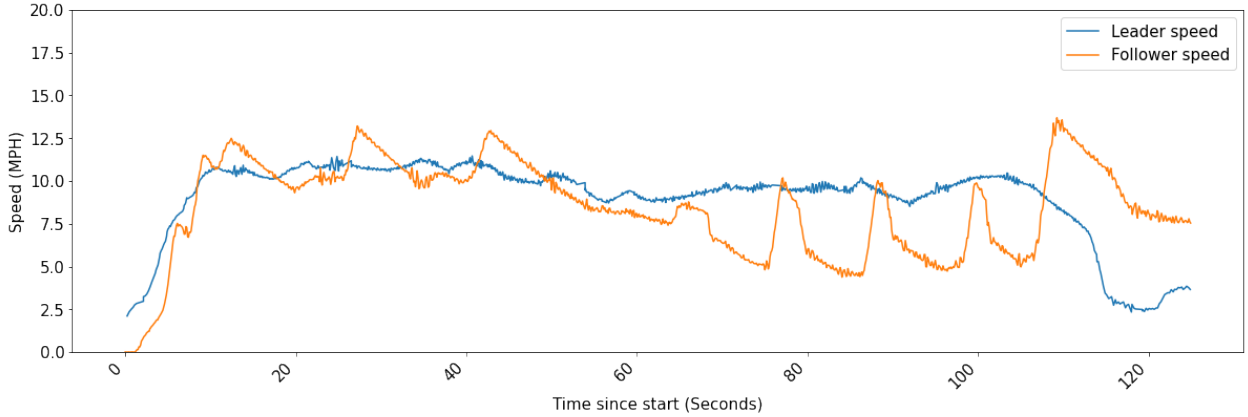
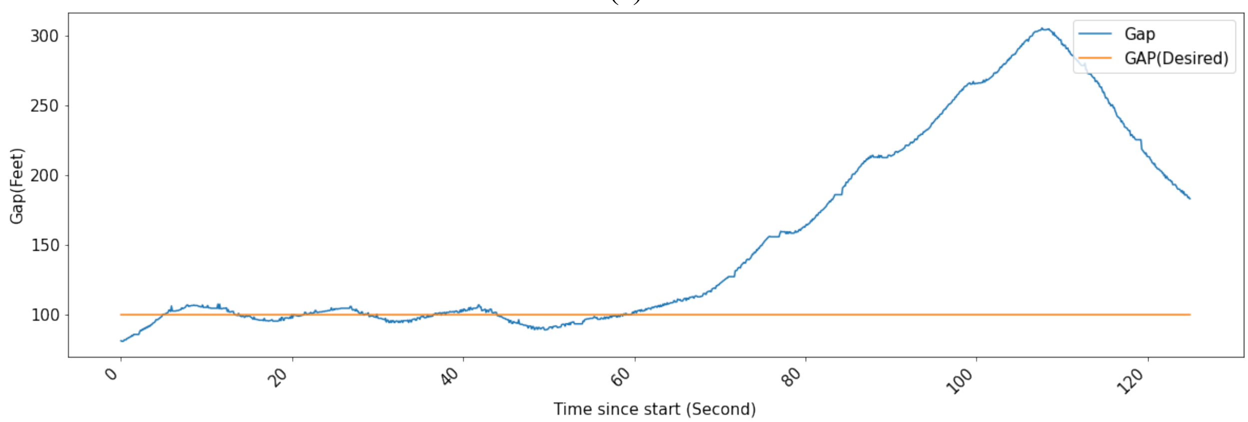


Figure B.27 Test case 8, Run 3a: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



(a)



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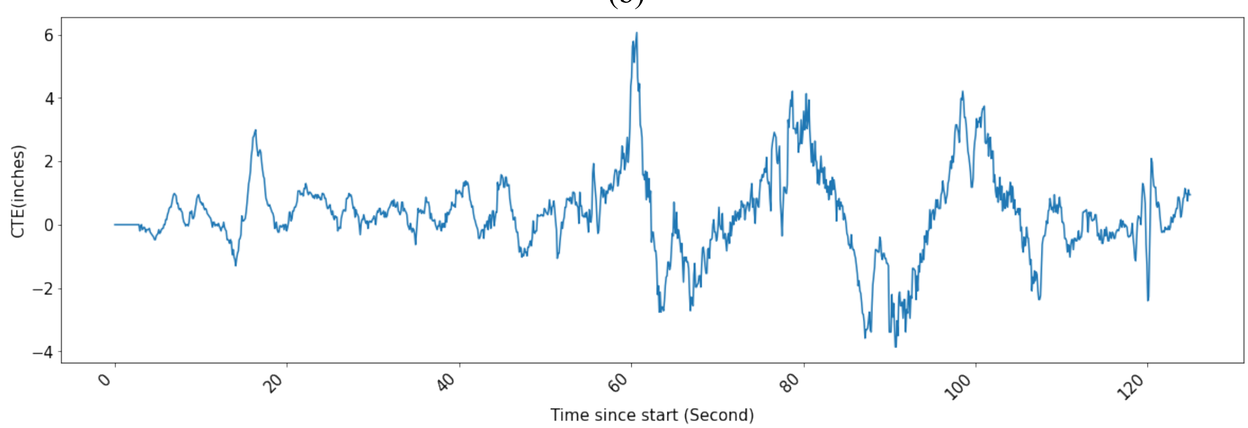
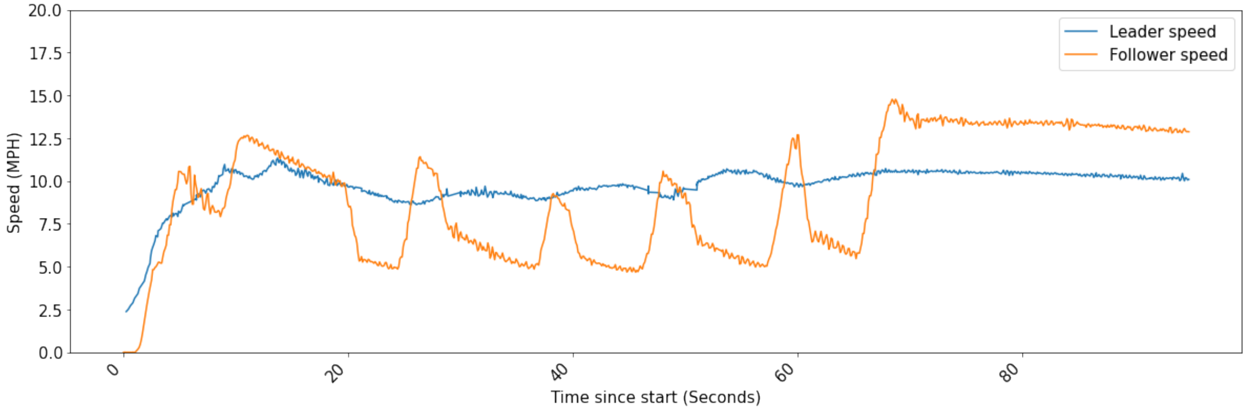
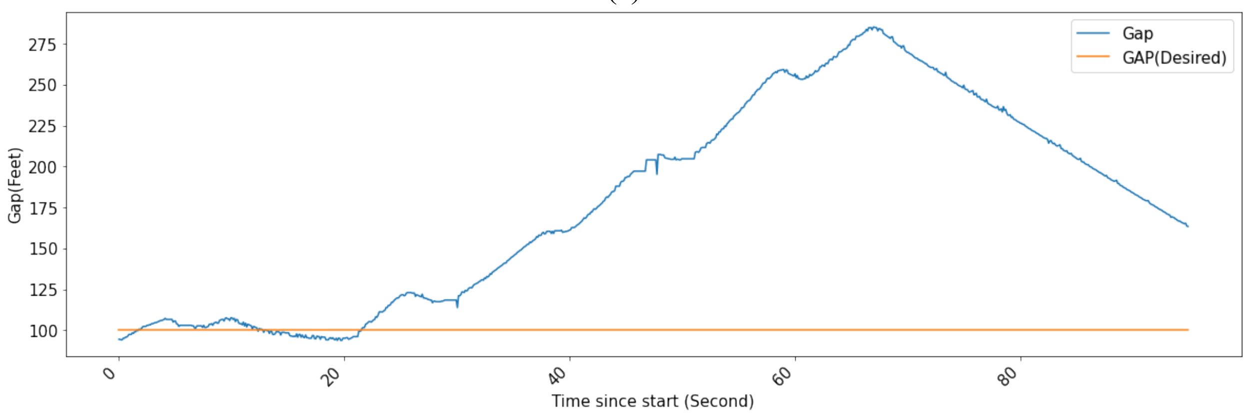


(c)

Figure B.28 Test case 8, Run 3b: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



(a)



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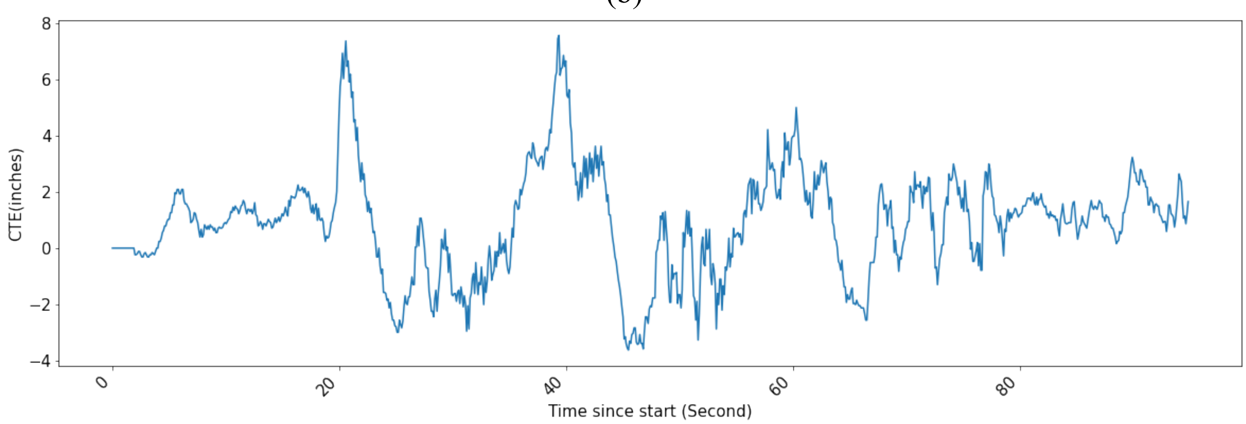
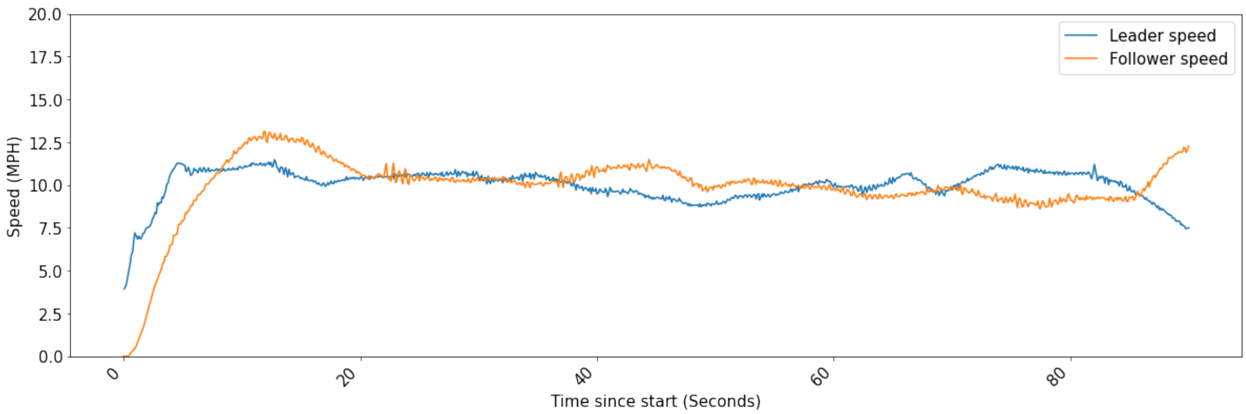


(c)

Figure B.29 Test case 8, Run 3c: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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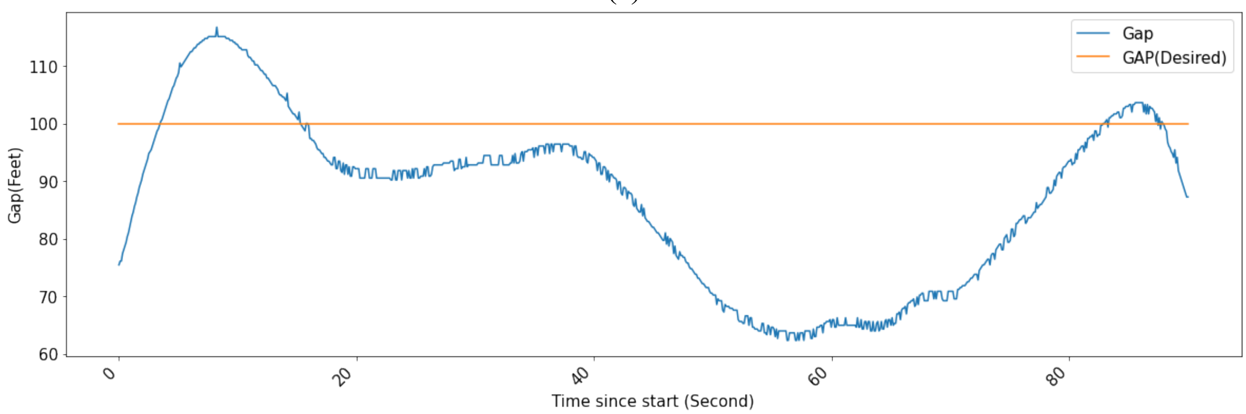
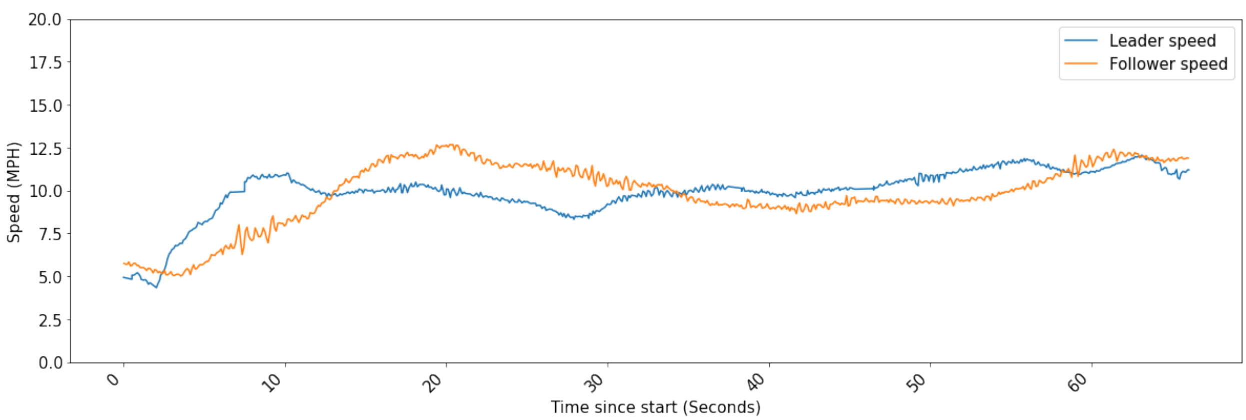
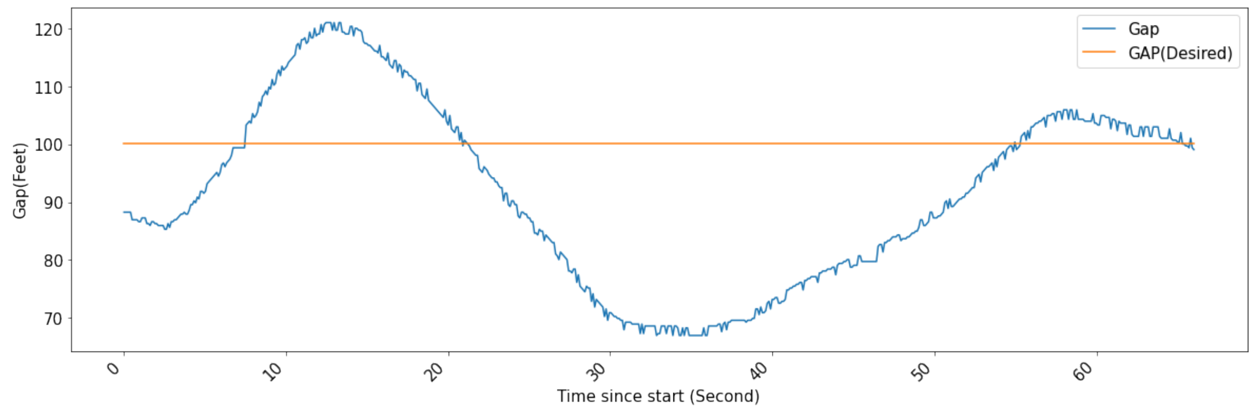


(b)

Figure B.30 Test case 8, Run 4a: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap.

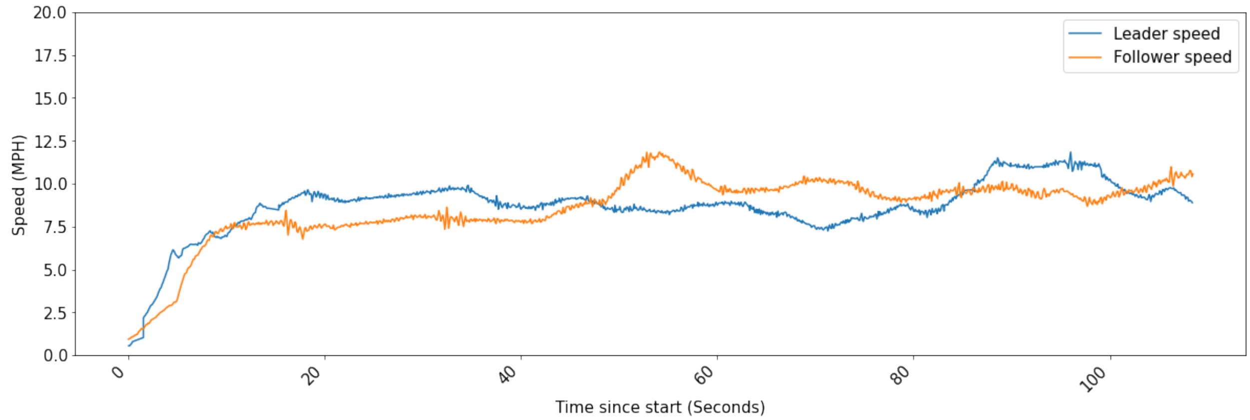


(a)

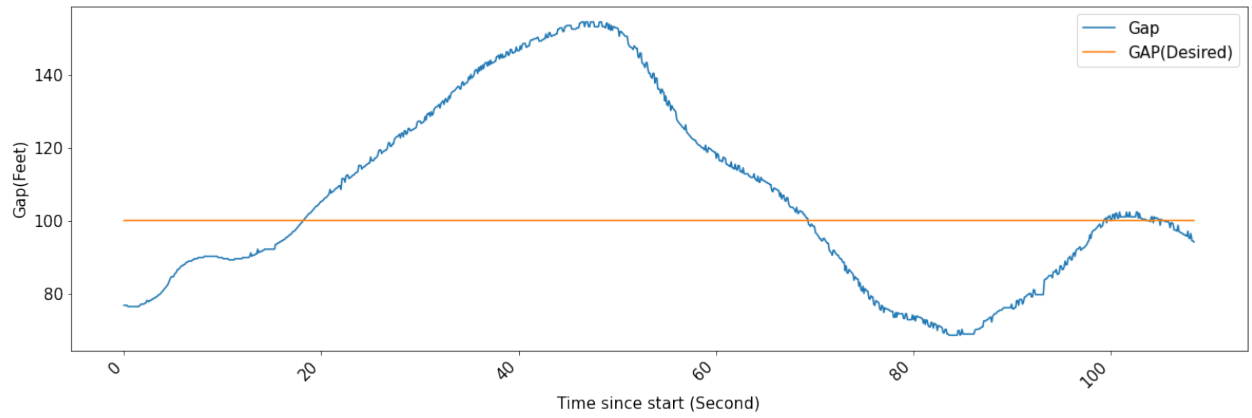


(b)

Figure B.31 Test case 8, Run 4b: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap.

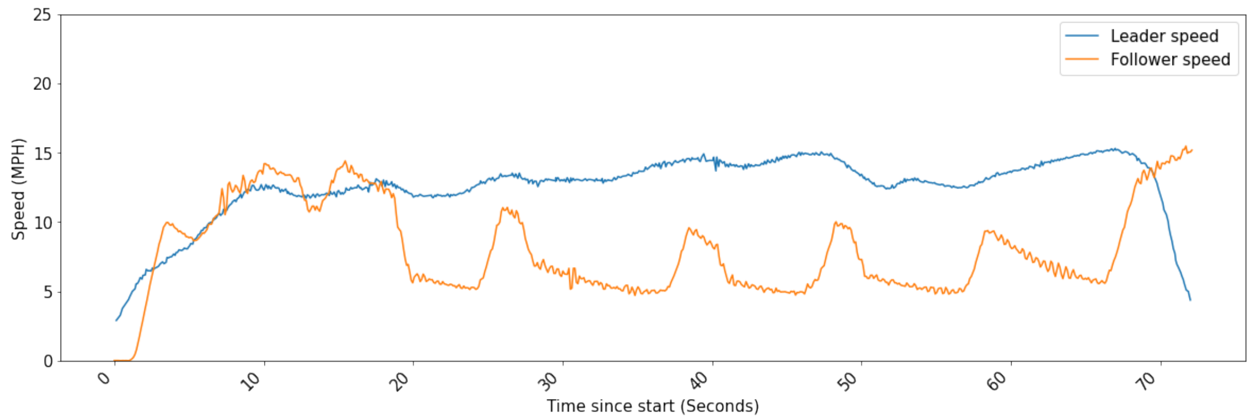


(a)



(b)

Figure B.32 Test case 8, Run 4c: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap.



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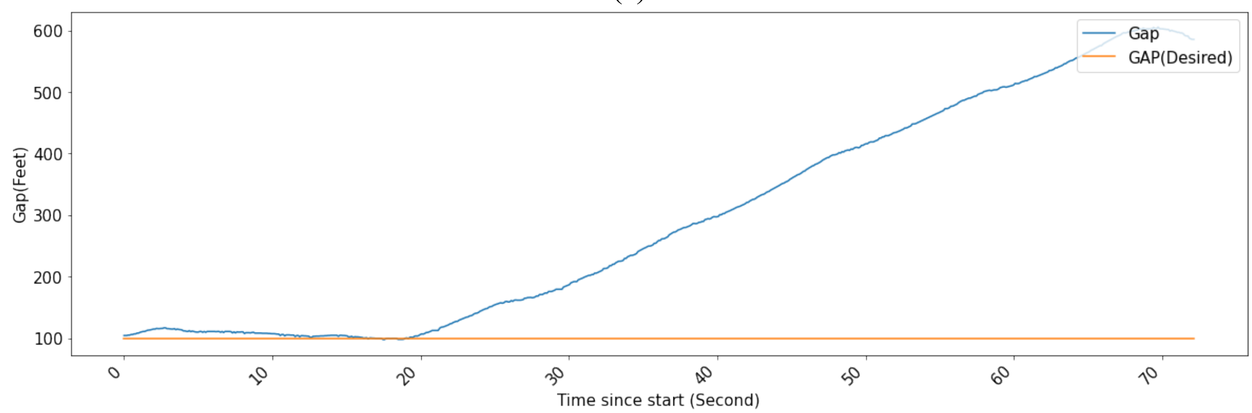

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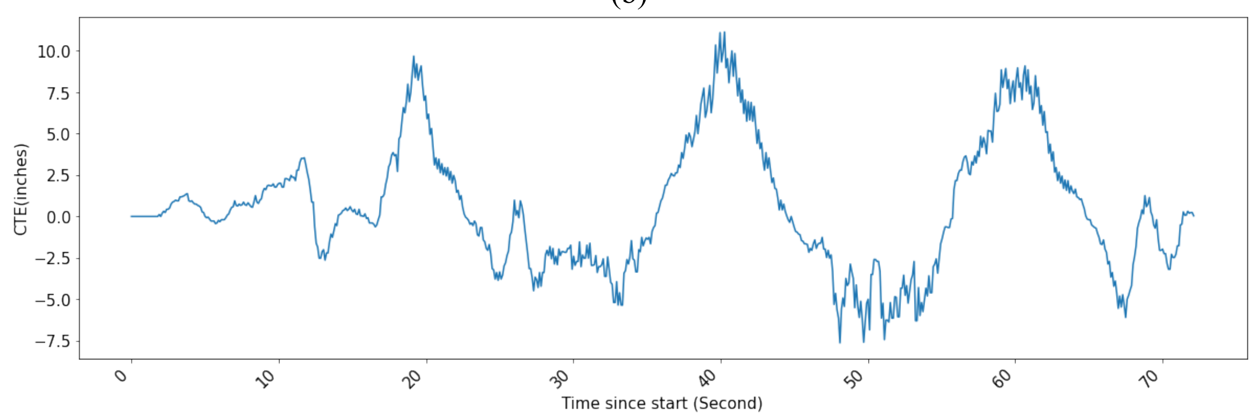
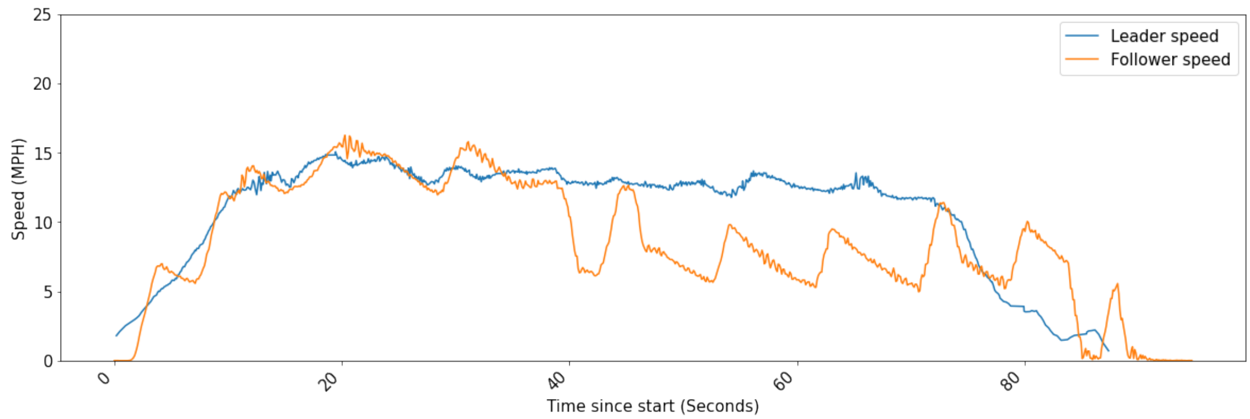


(c)

Figure B.33 Test case 8, Run 5a: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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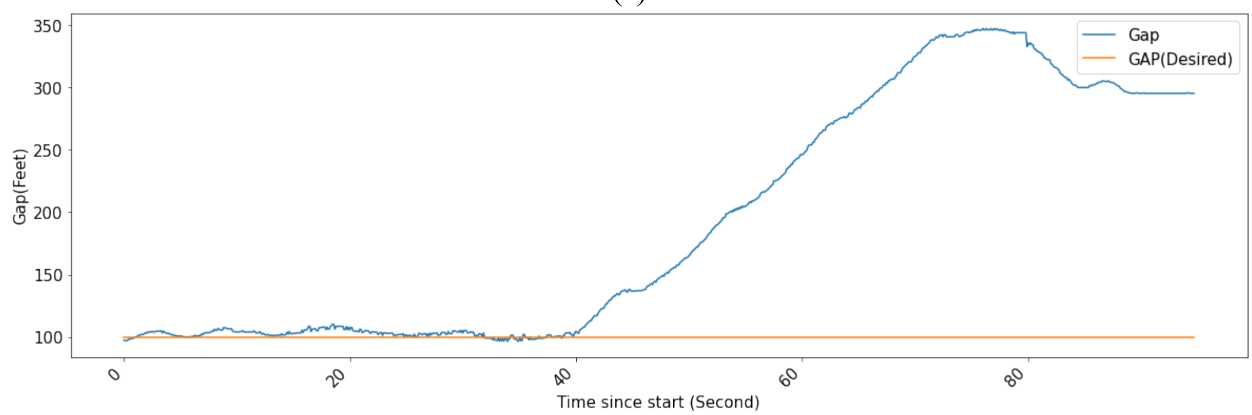

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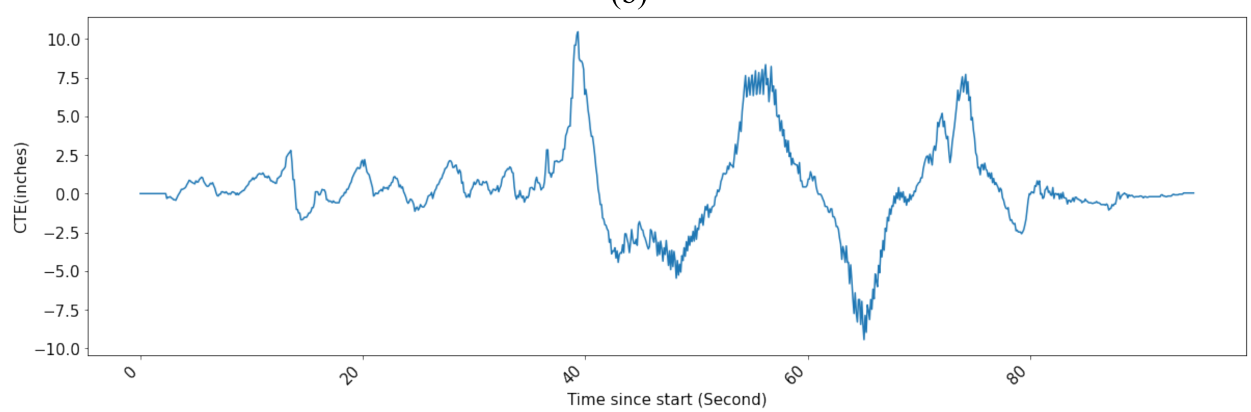
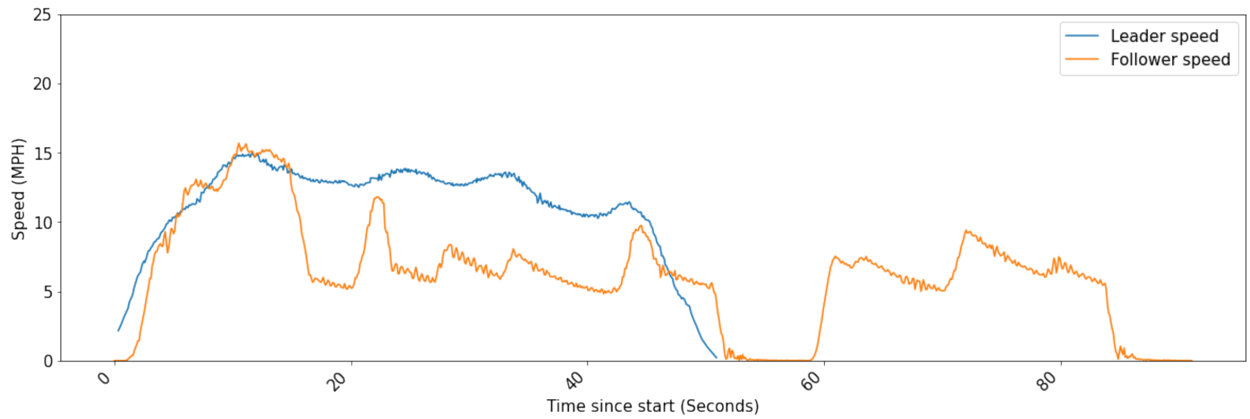


(c)

Figure B.34 Test case 8, Run 5b: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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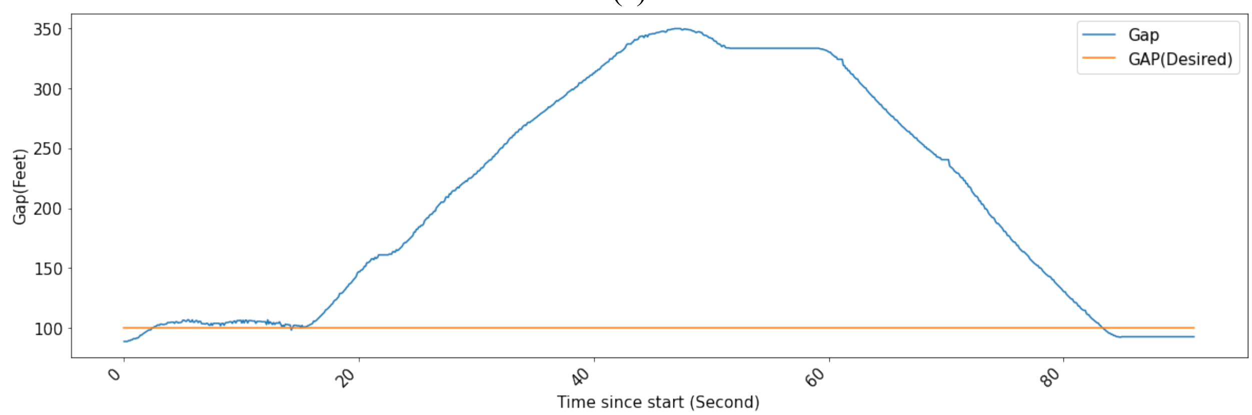

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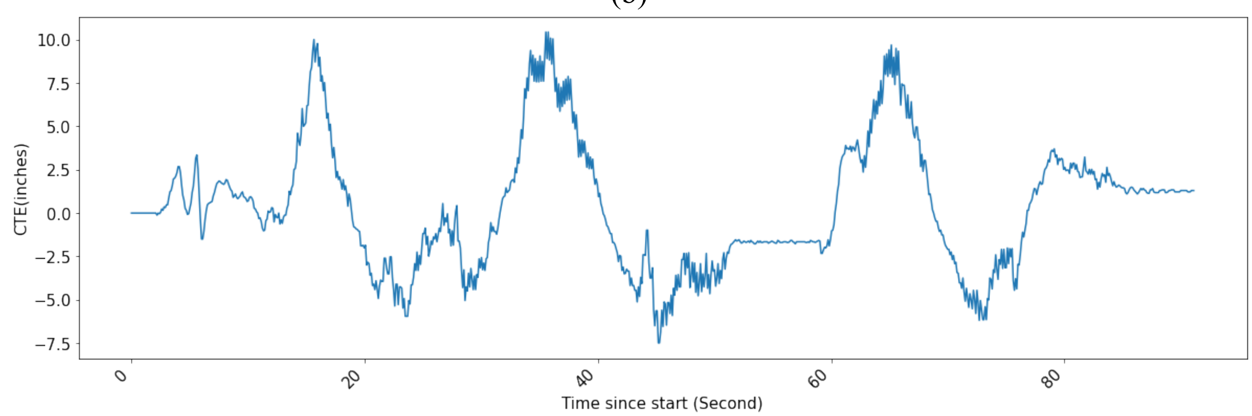
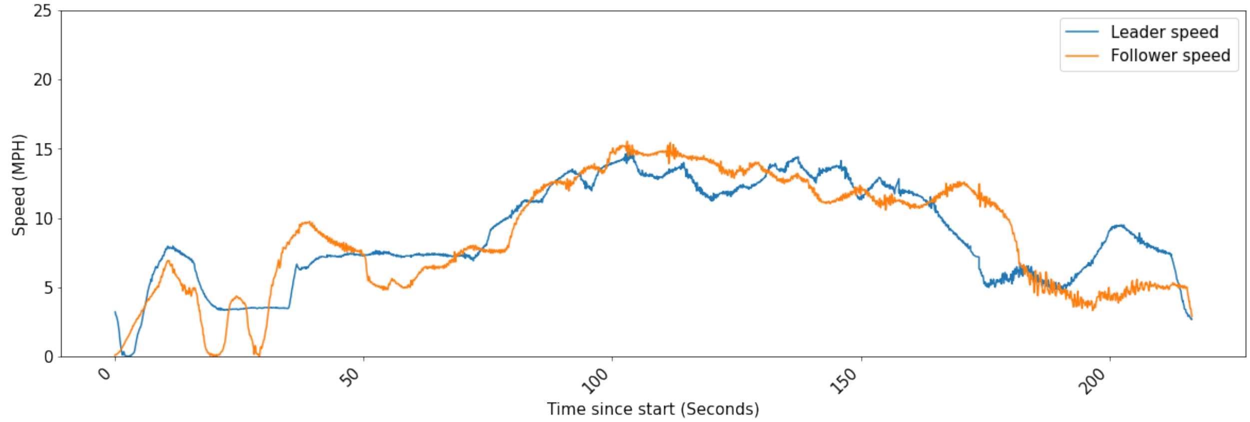


(c)

Figure B.35 Test case 8, Run 5c: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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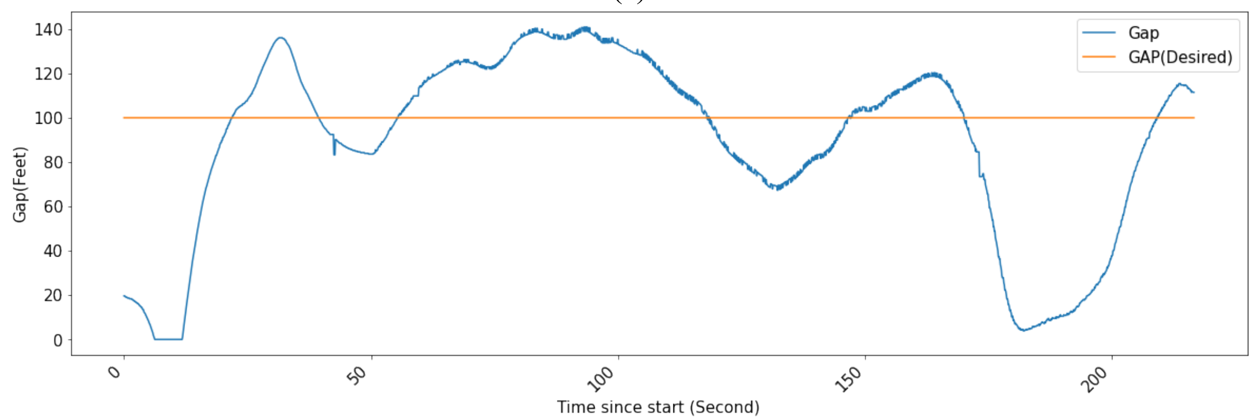

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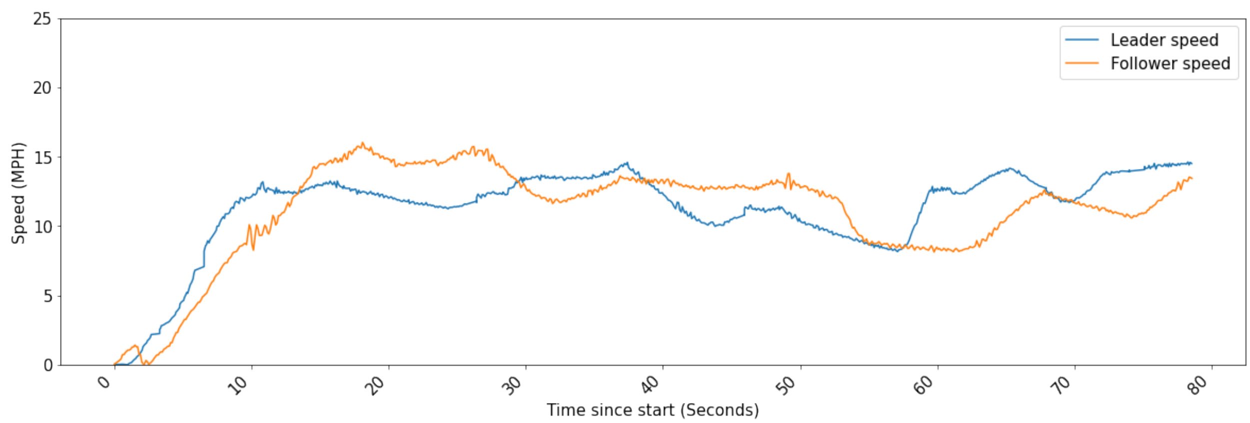
Figure B.36 Test case 8, Run 6a: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap.



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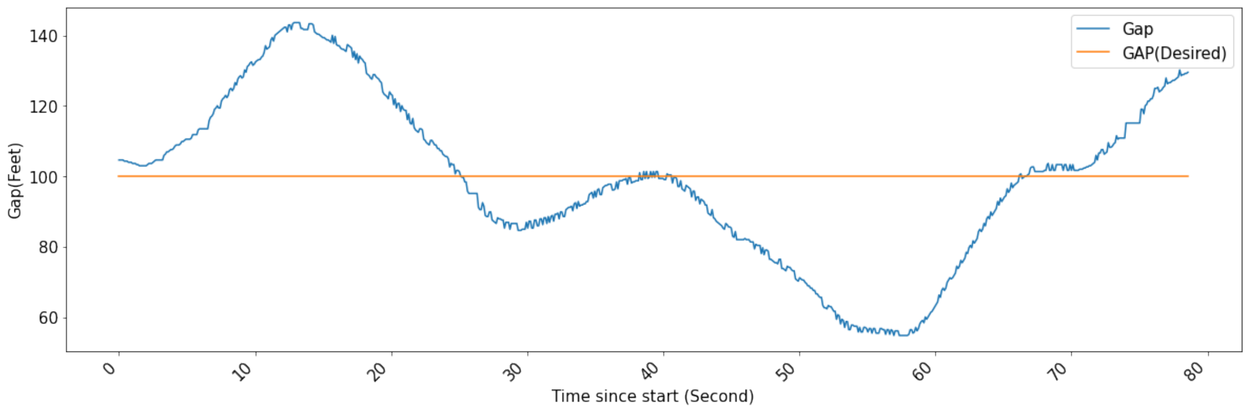

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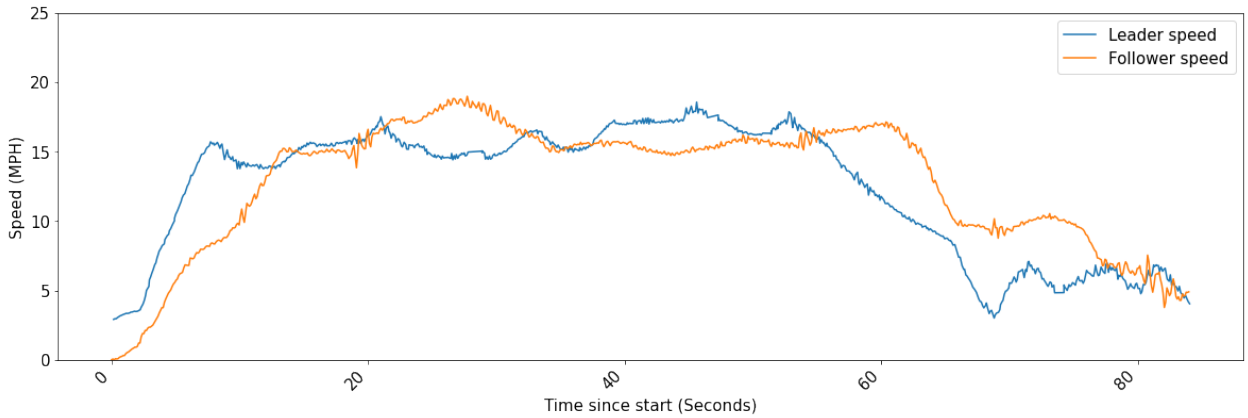
Figure B.37 Test case 8, Run 6b: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap.



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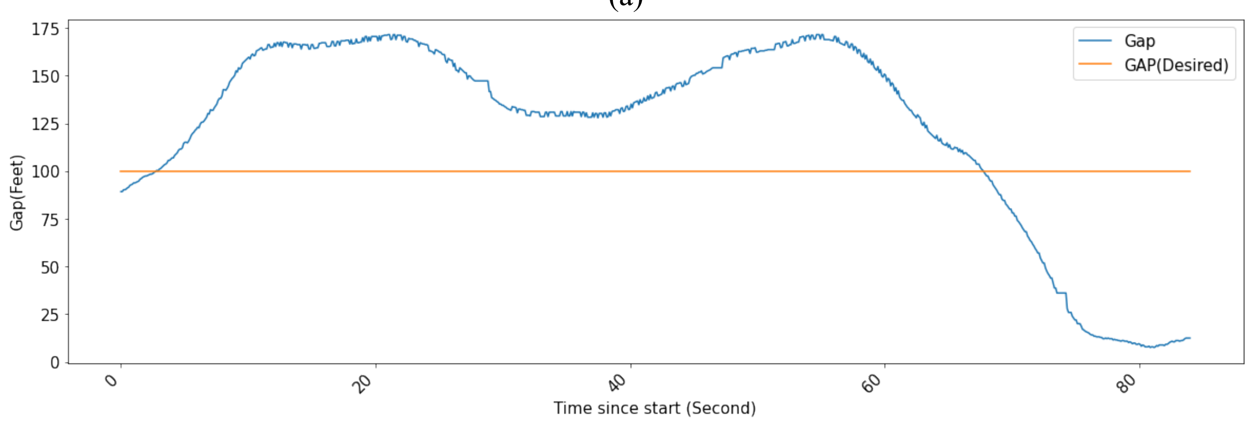


(b)

Figure B.38 Test case 8, Run 6c: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap.

B.3 Focus Area 3: Lateral Accuracy

Test Case 9: Lane Change

Table B.21 Test Procedure-Test Case 9

Pre-procedure	• Placed six cones in a straight line with 100 feet in-between distance. • Removed the cones between 200 feet to 400 feet for lane change operation.
Operation procedure	• Activated the leader truck and ATMA and set the gap to 100 feet and perform lane changing at 5 mph from right to left. • Repeated the test with the left-side lane closed. • Repeated the test at the speed of 10 mph and 15 mph. • Conducted 3 runs for each speed.
Data collection	• Collected ATMA log files.
Expected results	The ATMA maintains a lateral accuracy of ±6 inches during lane change operations.
Total number of runs	18 runs
Supporting equipment	Walkie-talkie, Traffic cones

All 18 runs were performed successfully. The gap difference and CTE are shown in Table B.22 and Table B.23, respectively. The results show the CTE is larger than ±6 inches in runs 11, 17, and 18. Figure B.39 to Figure B.56 show the leader speed and follower speed, gap difference, and CTE for each run under case 9.

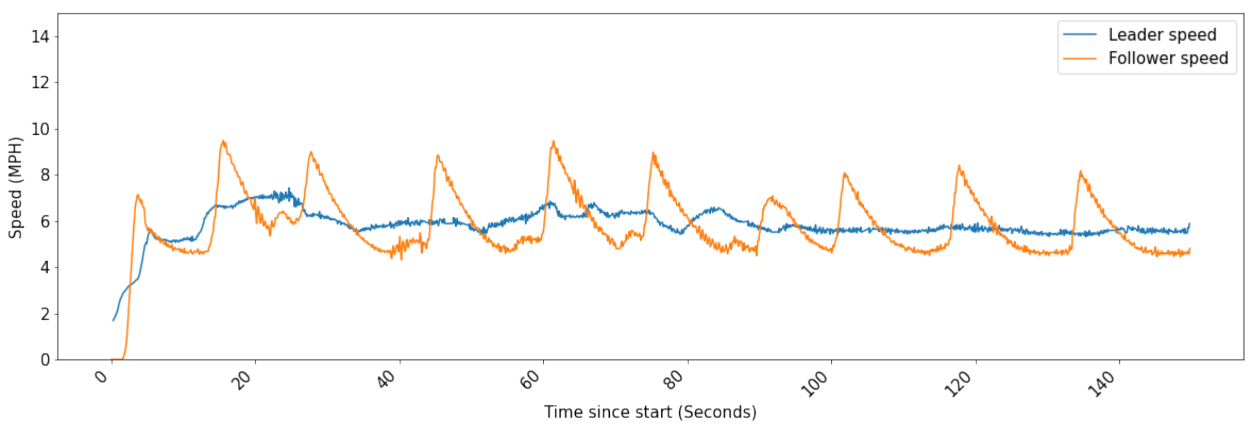
Table B.22 Gap difference for each run: Case 9

Runs	Test Speed	Lane Changing Direction	Gap difference Max (feet)	Min (feet)	Mean (feet)	Std. (feet)
1	5 mph	Right → Left	6.234	-8.858	-1.344	3.939
2	5 mph	Left → Right	14.108	-10.499	-1.190	4.596
3	5 mph	Right → Left	18.373	-12.139	-0.867	5.143
4	5 mph	Left → Right	8.858	-10.499	-3.162	3.474
5	5 mph	Right → Left	4.593	-14.763	-2.225	4.441
6	5 mph	Left → Right	6.890	-16.404	-3.162	5.491
7	10 mph	Right → Left	98.425	-14.108	13.878	30.669
8	10 mph	Left → Right	15.0919	-13.780	-2.0524	6.467
9	10 mph	Right → Left	9.842	-15.420	-2.0952	4.298
10	10 mph	Left → Right	6.562	-13.123	-1.492	4.958
11	10 mph	Right → Left	16.404	-12.467	-0.115	6.276
12	10 mph	Left → Right	8.532	-12.139	-0.0843	3.237
13	15 mph	Right → Left	10.499	-4.921	1.845	3.151
14	15 mph	Left → Right	9.842	-8.202	2.383	3.0538
15	15 mph	Right → Left	10.499	-7.546	2.106	3.0833

16	15 mph	Left → Right	8.858	-11.483	0.724	4.950
17	15 mph	Right → Left	14.436	-12.795	1.965	5.689
18	15 mph	Left → Right	11.811	-26.903	0.274	9.200

Table B.23. CTE: Case 9

Runs	Test Speed	Lane Changing Direction	CTE (Inches)			
			Max	Min	Mean	Std.
1	5 mph	Right → Left	2.874	-2.362	0.543	0.678
2	5 mph	Left → Right	3.149	-1.142	0.790	0.716
3	5 mph	Right → Left	2.913	-2.598	0.402	0.682
4	5 mph	Left → Right	3.268	-3.543	0.603	0.755
5	5 mph	Right → Left	3.189	-1.732	0.427	0.663
6	5 mph	Left → Right	3.780	-2.992	0.552	0.890
7	10 mph	Right → Left	4.173	-2.244	0.495	0.930
8	10 mph	Left → Right	3.0315	-0.984	1.0527	0.759
9	10 mph	Right → Left	4.370	-3.346	0.410	0.9803
10	10 mph	Left → Right	3.937	-1.850	0.771	0.884
11	10 mph	Right → Left	6.732	-5.354	0.251	1.296
12	10 mph	Left → Right	4.055	-1.732	0.858	0.969
13	15 mph	Right → Left	4.685	-4.0551	0.797	1.241
14	15 mph	Left → Right	5.630	-2.795	1.524	1.372
15	15 mph	Right → Left	4.0158	-3.661	0.769	1.167
16	15 mph	Left → Right	4.881	-0.945	1.580	1.0864
17	15 mph	Right → Left	8.0315	-4.0945	0.808	1.564
18	15 mph	Left → Right	7.913	-2.283	1.353	1.379



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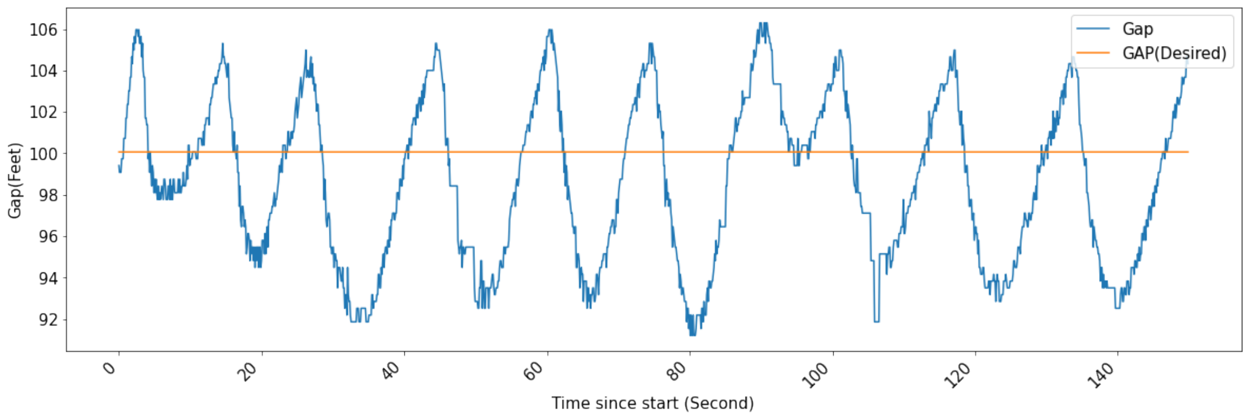

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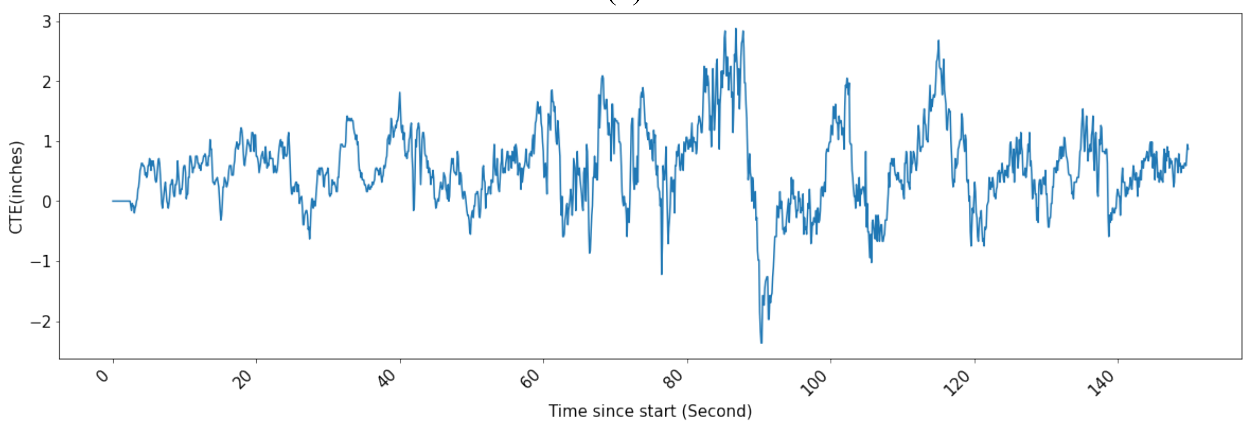
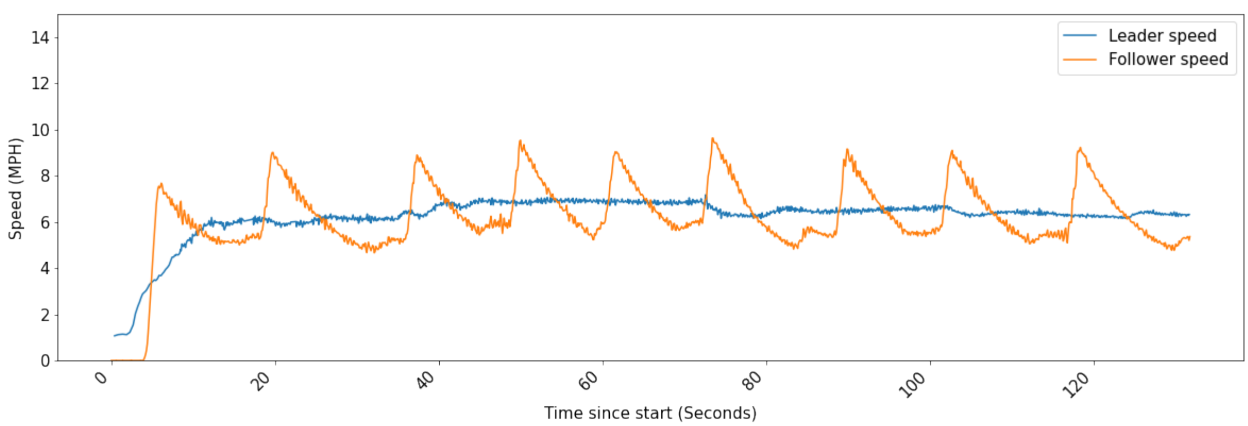


(c)

Figure B.39 Test case 9, Run 1: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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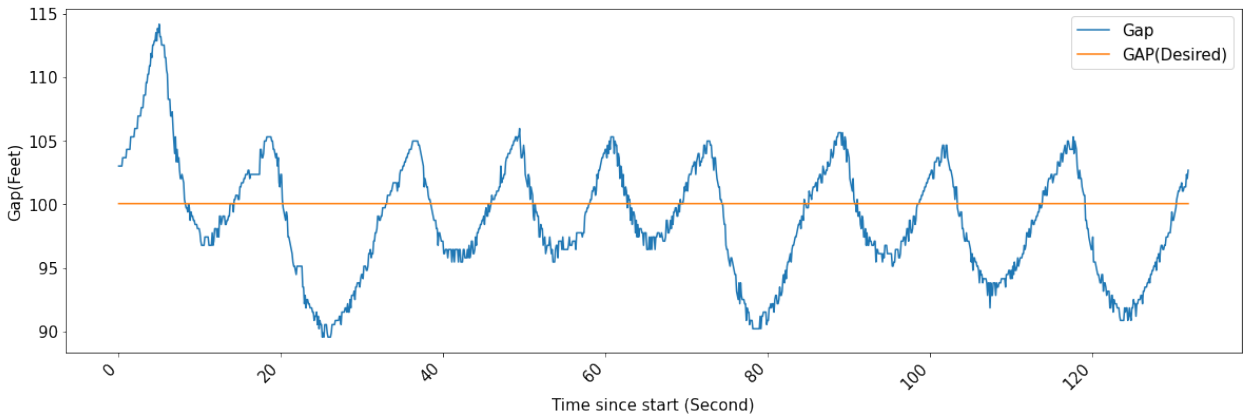

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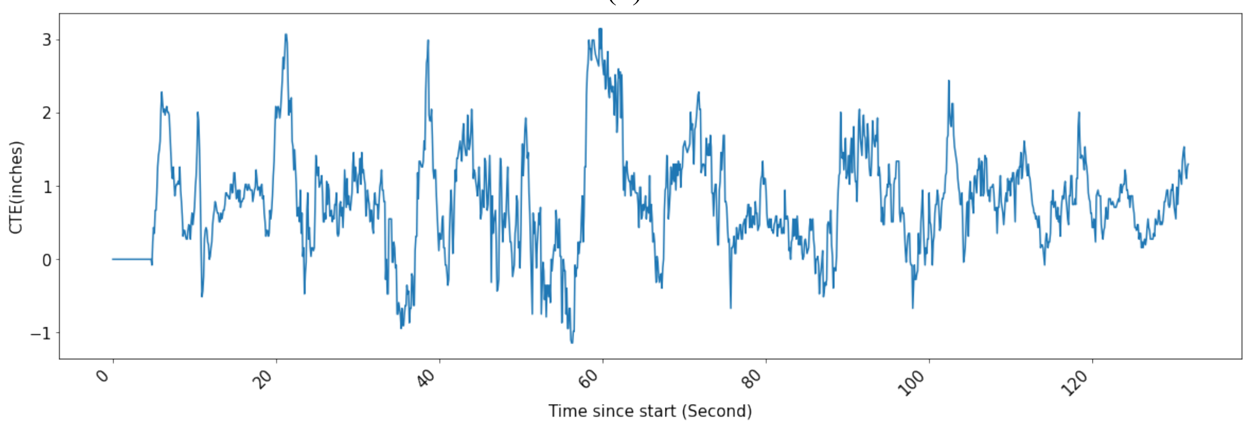

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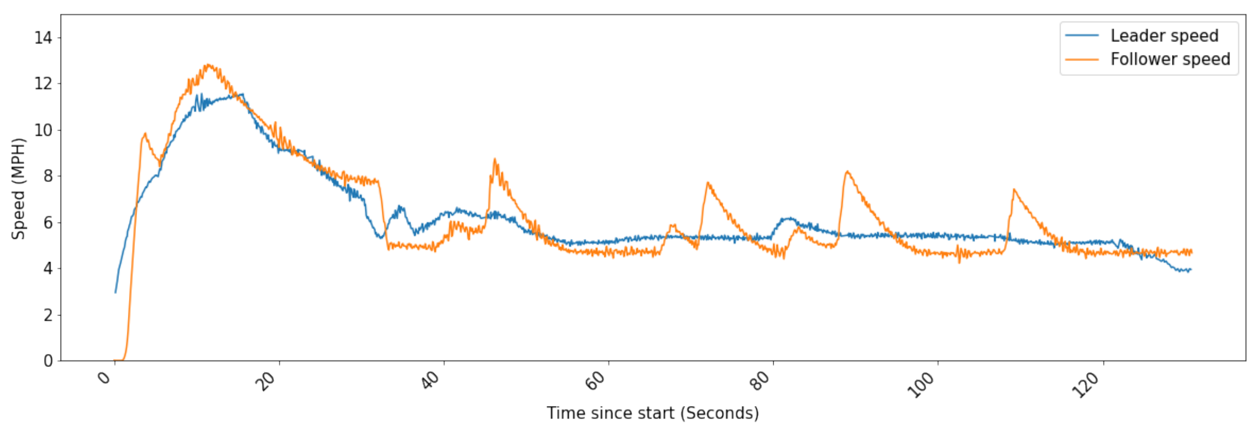
Figure B.40 Test case 9, Run 2: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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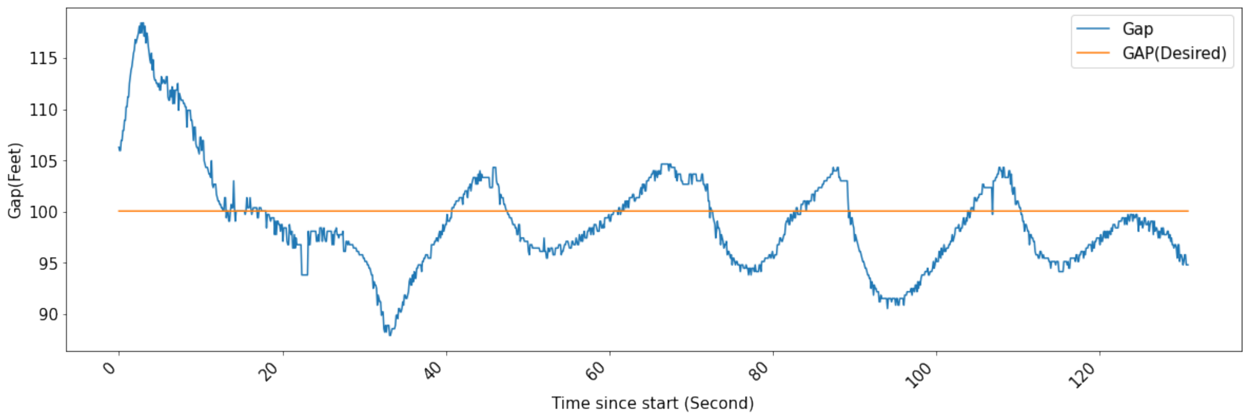

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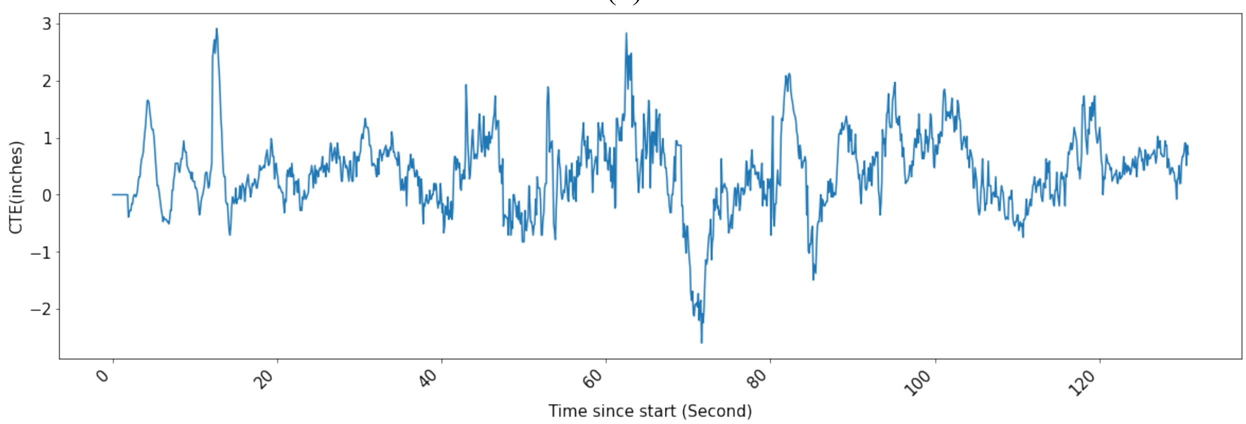
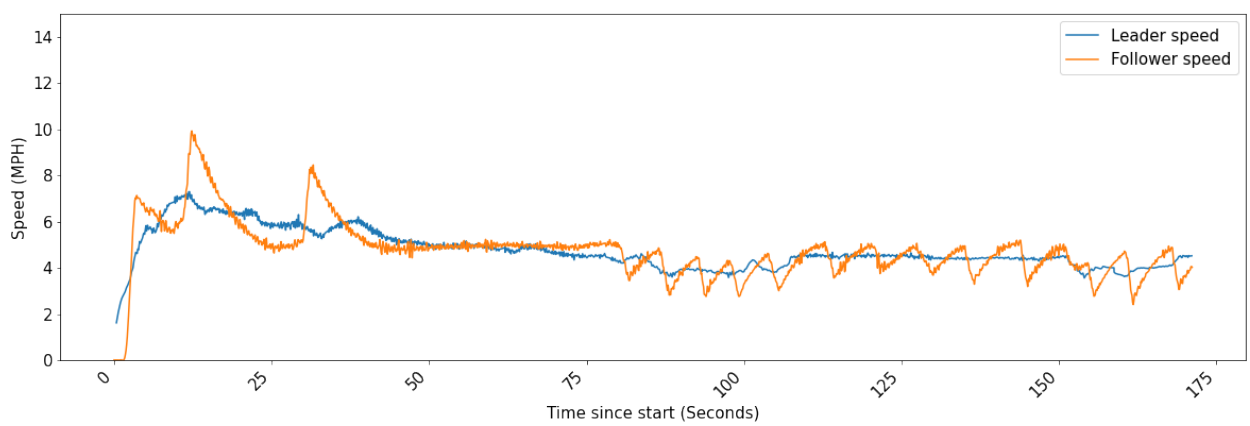


(c)

Figure B.41 Test case 9, Run 3: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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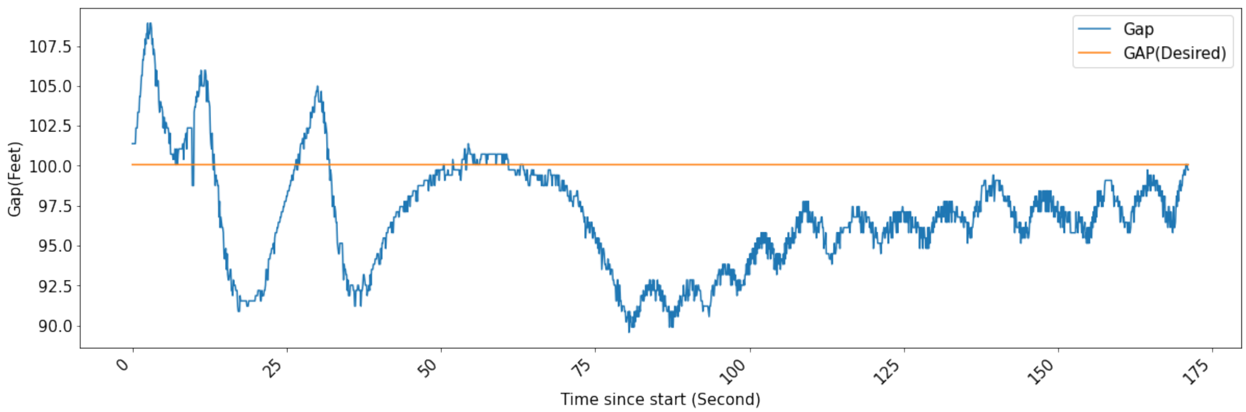

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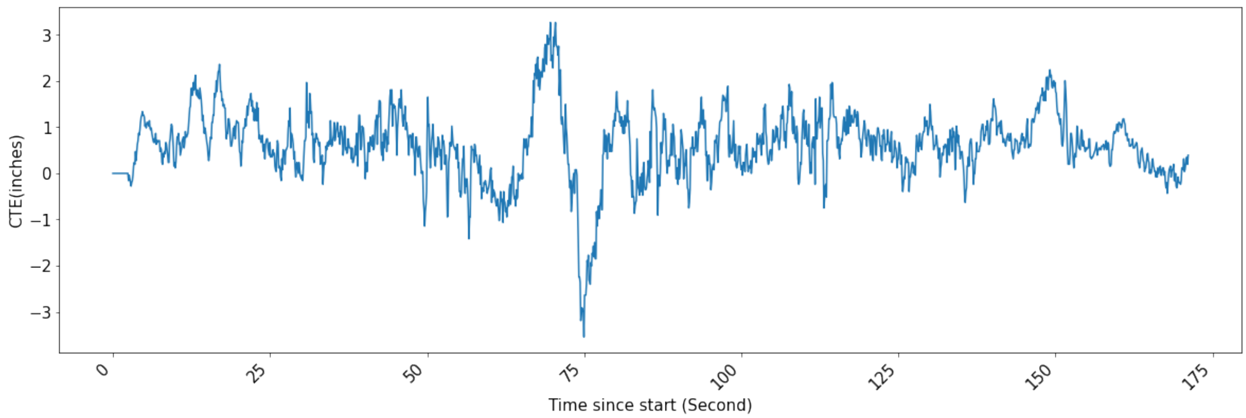
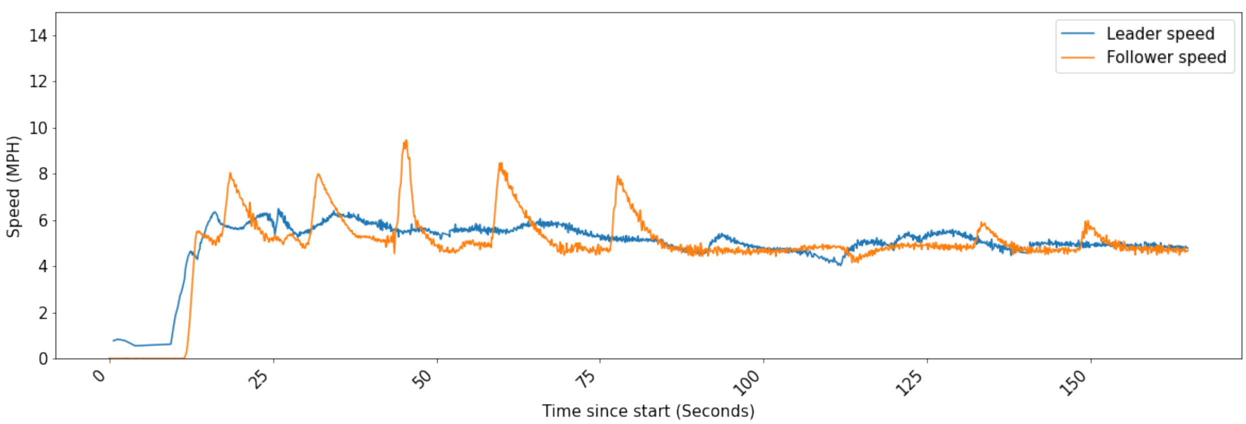


(c)

Figure B.42 Test case 9, Run 4: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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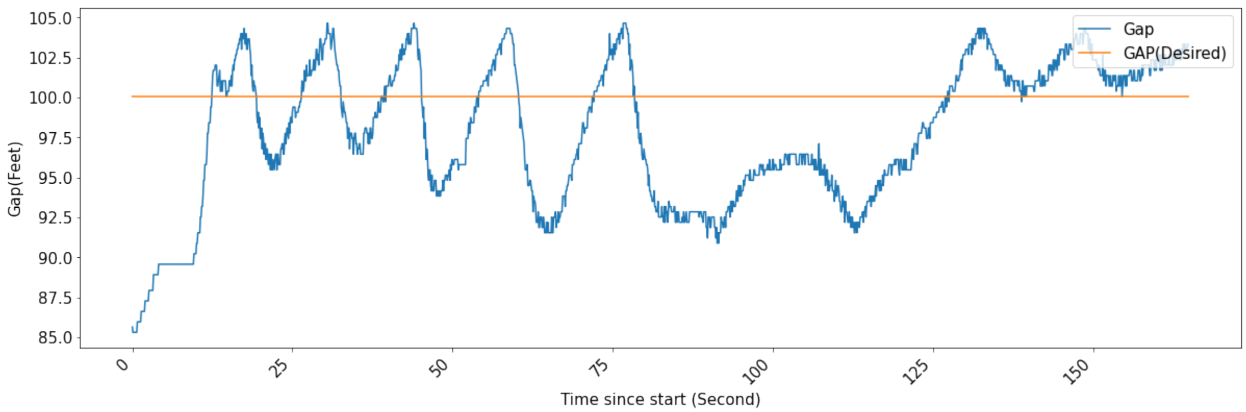

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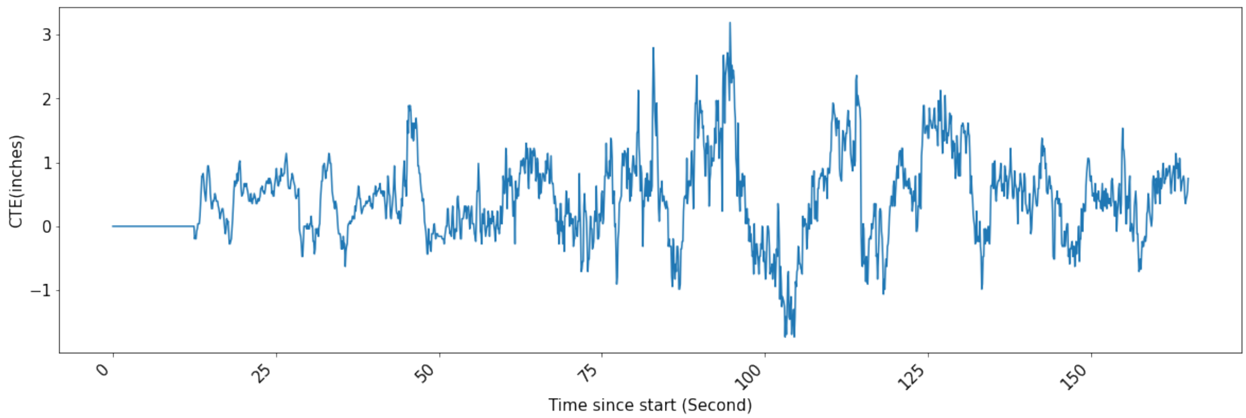
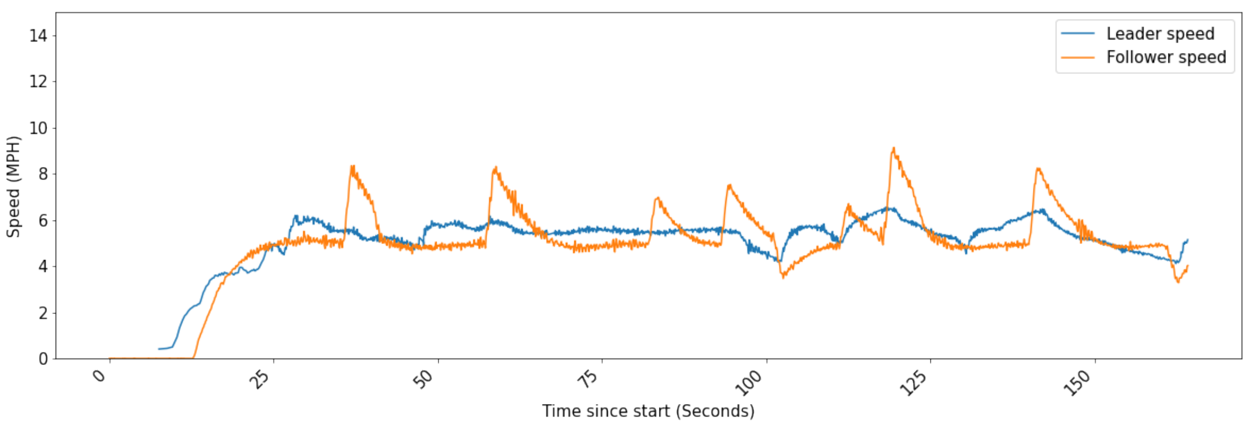


(c)

Figure B.43 Test case 9, Run 5: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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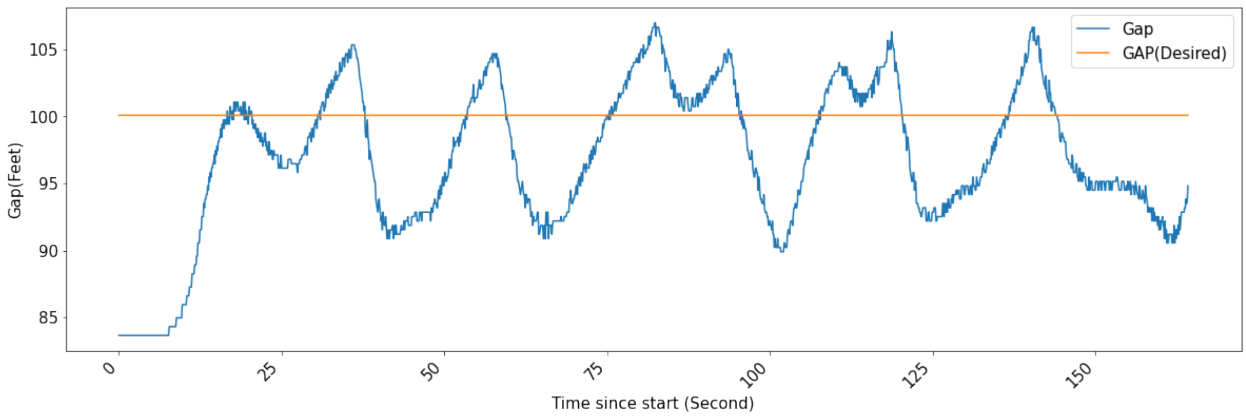

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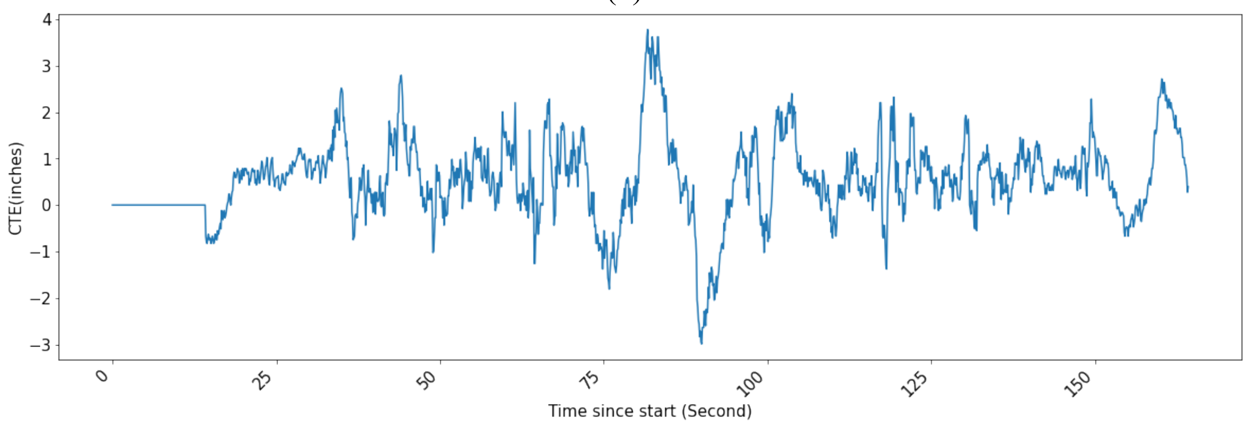
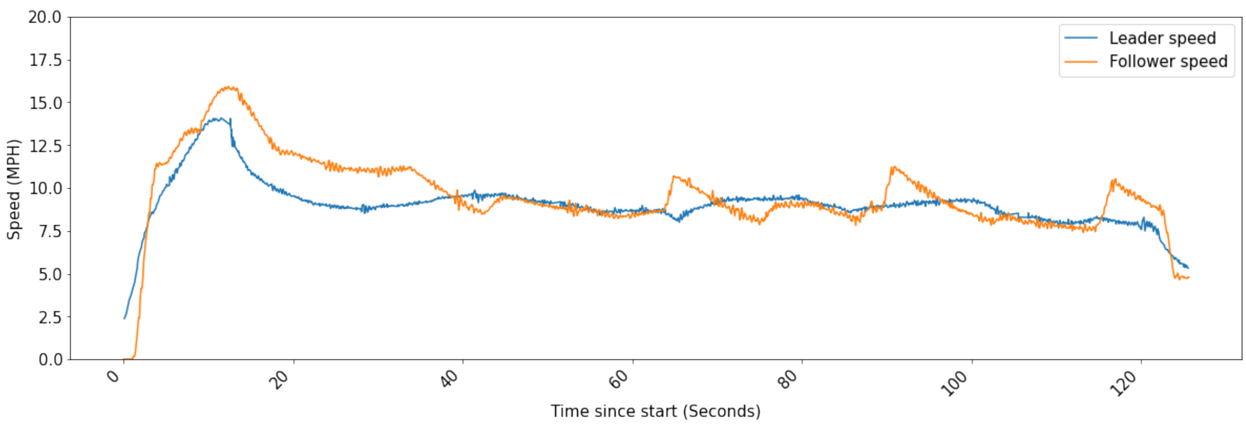


(c)

Figure B.44 Test case 9, Run 6: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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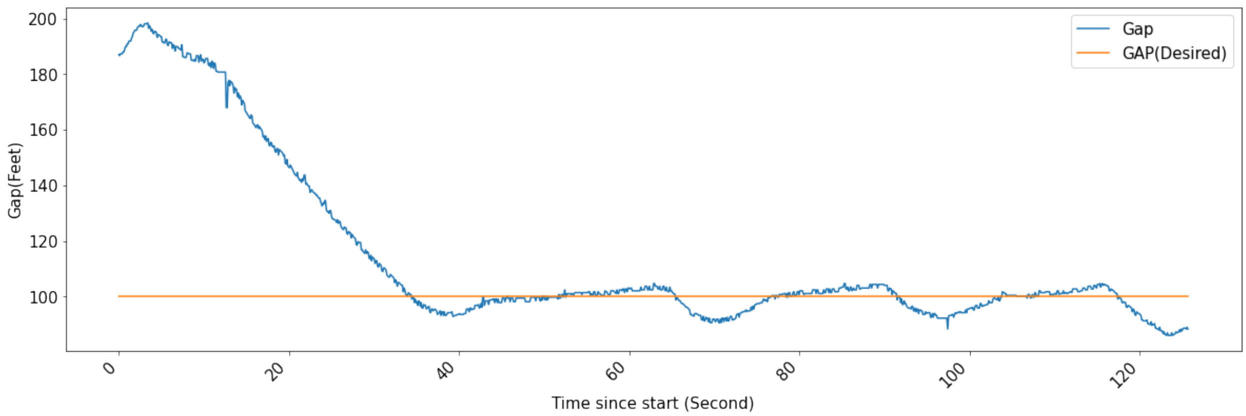

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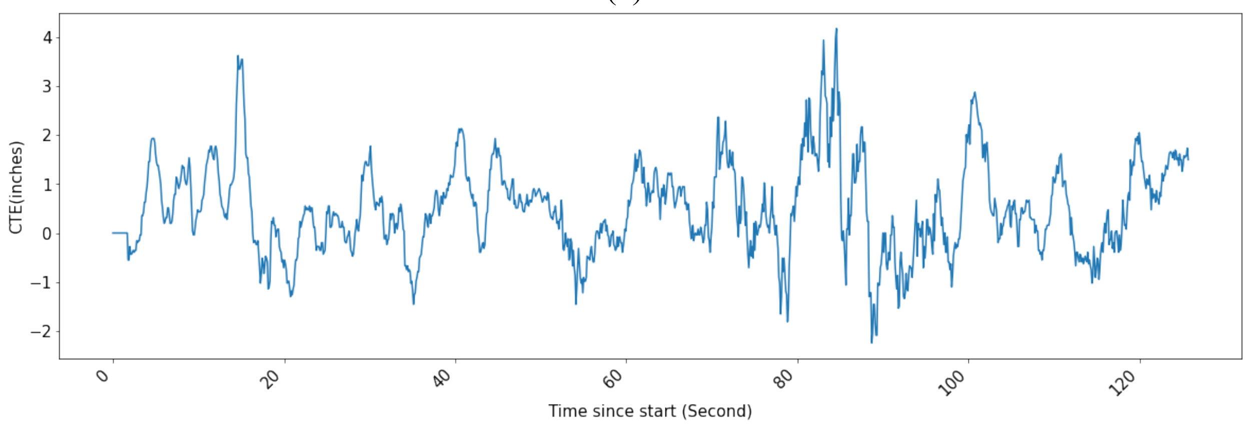
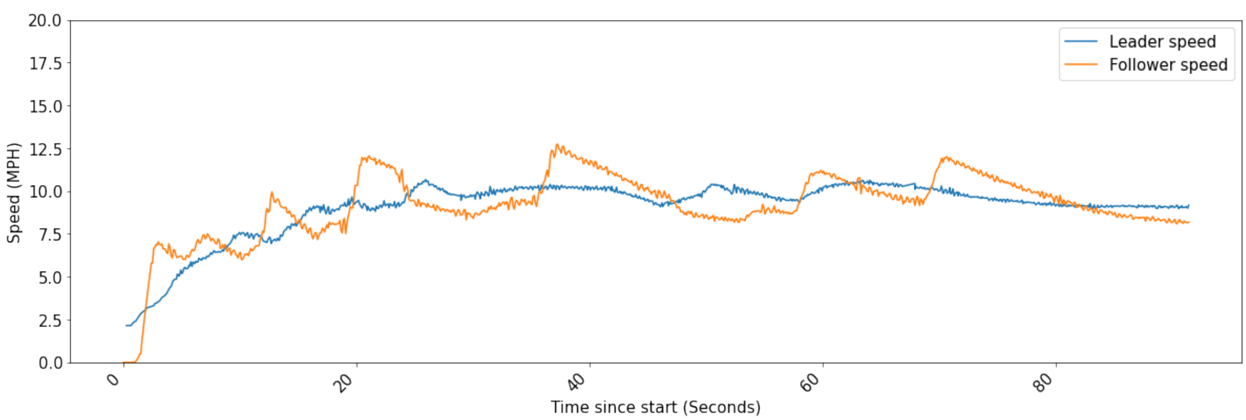


(c)

Figure B.45 Test case 9, Run 7: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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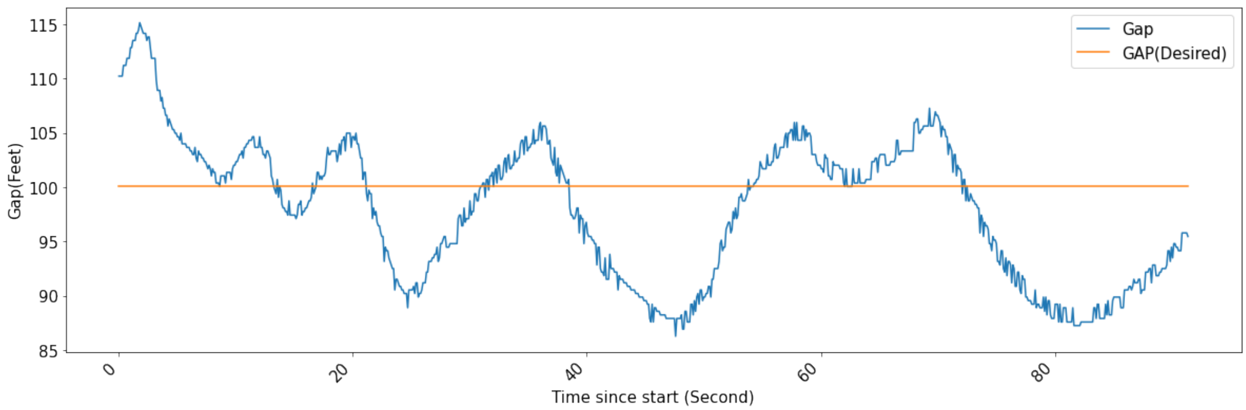

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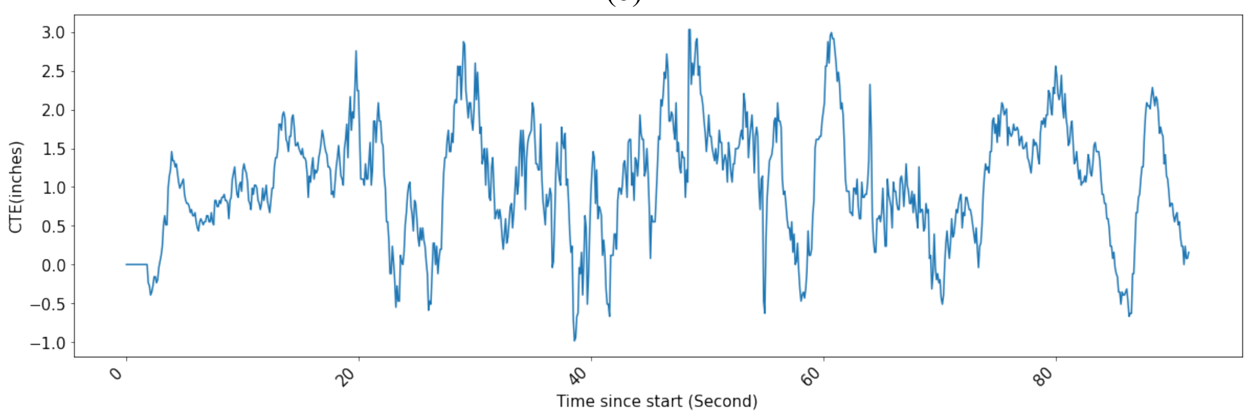

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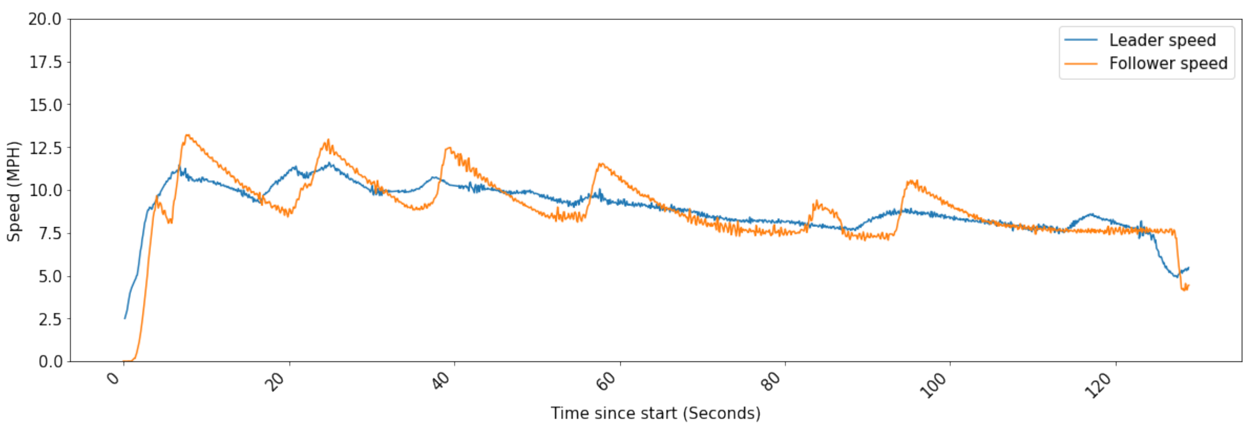
Figure B.46 Test case 9, Run 8: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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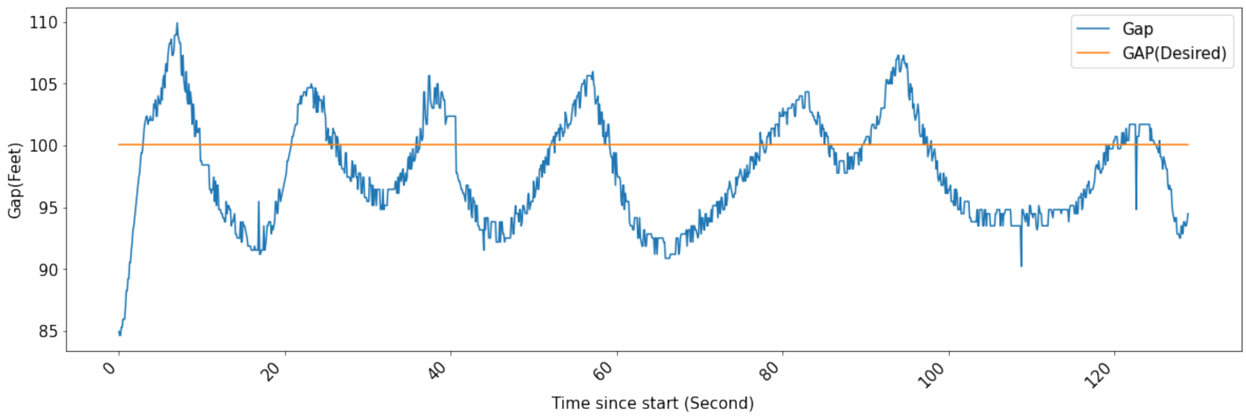

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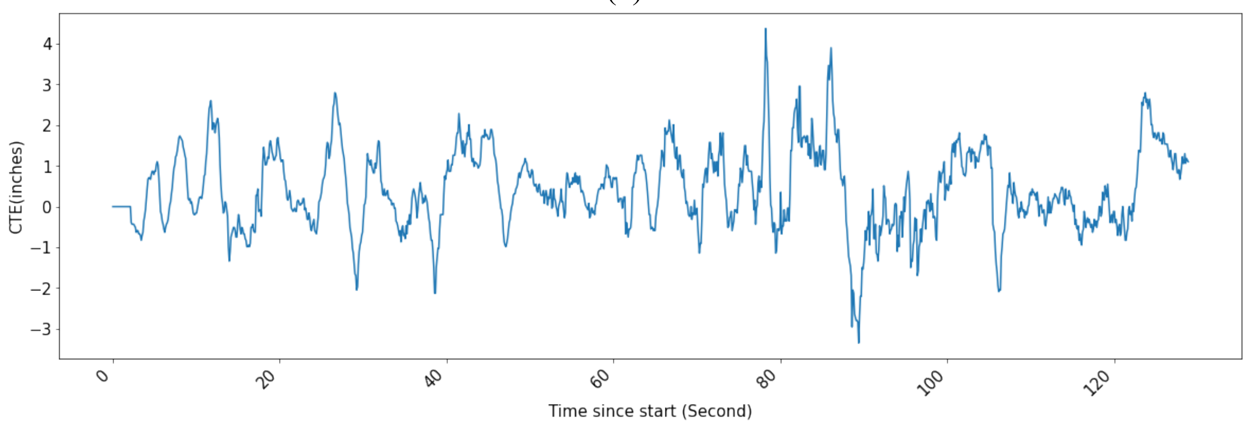
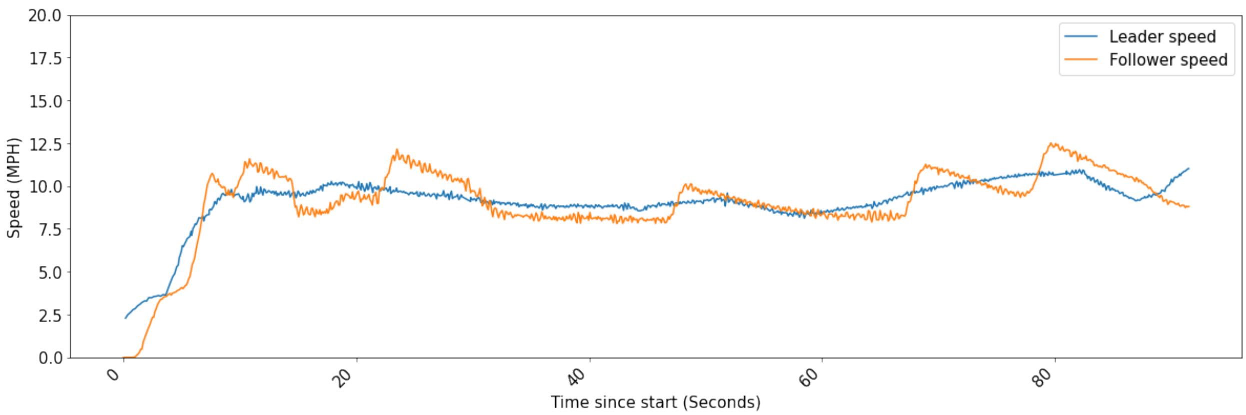


(c)

Figure B.47 Test case 9, Run 9: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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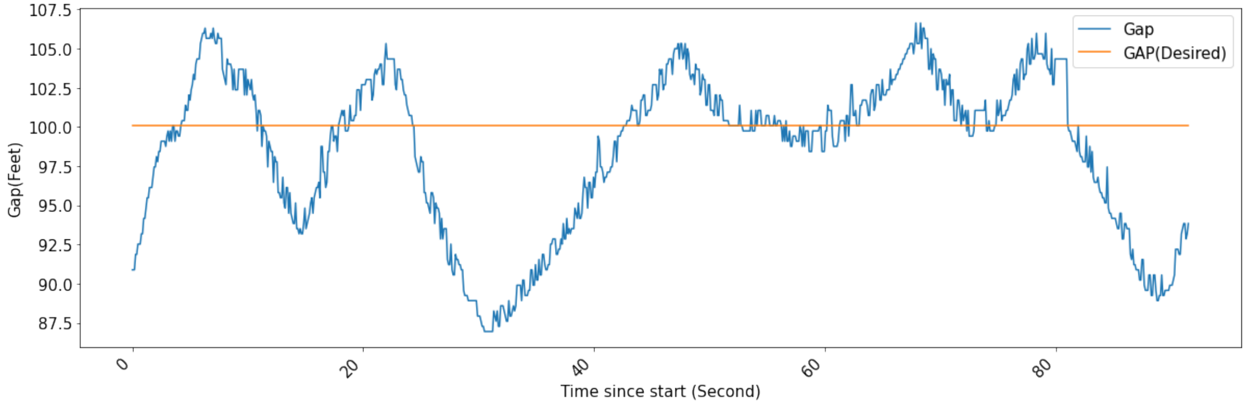

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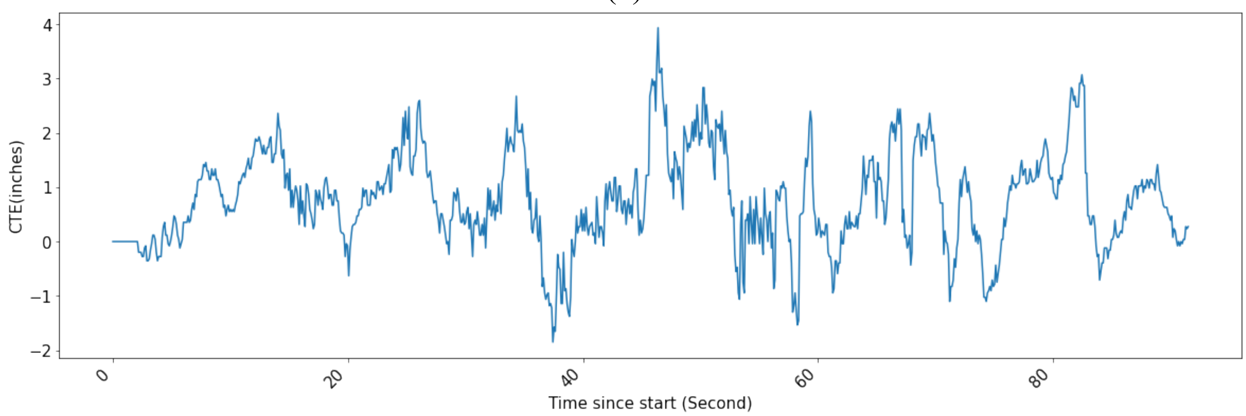
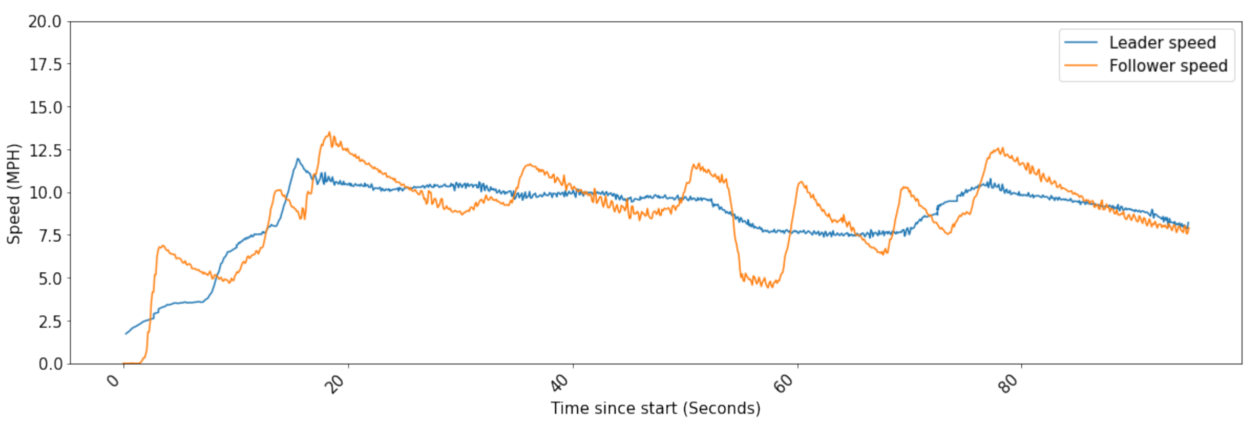


(c)

Figure B.48 Test case 9, Run 10: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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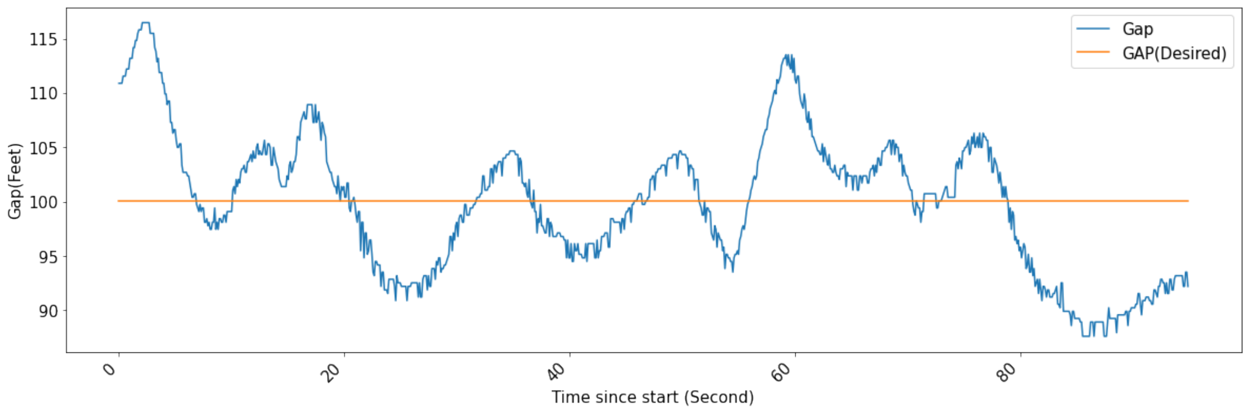

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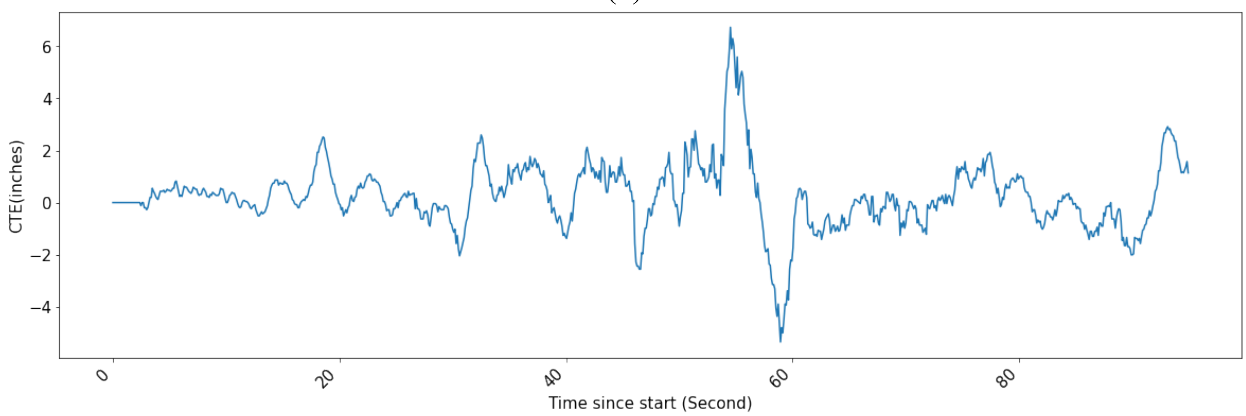
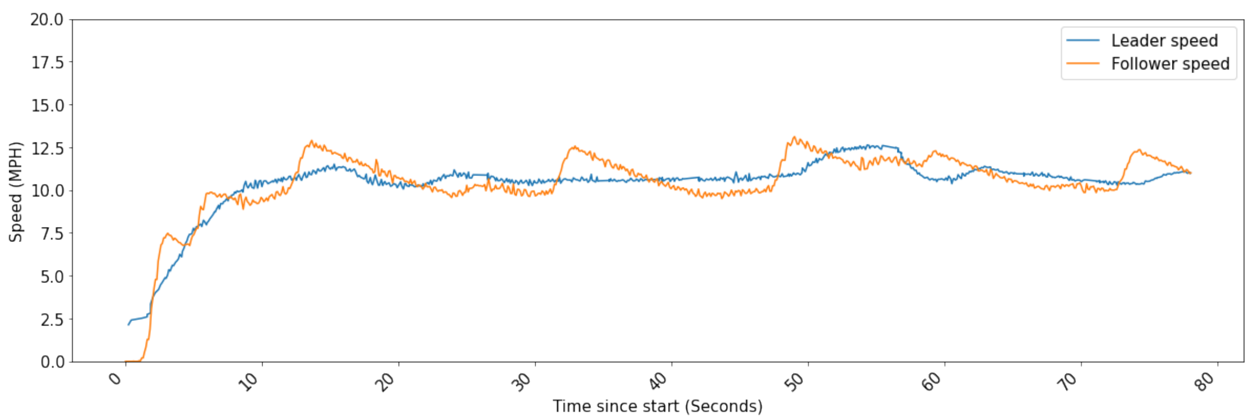


(c)

Figure B.49 Test case 9, Run 11: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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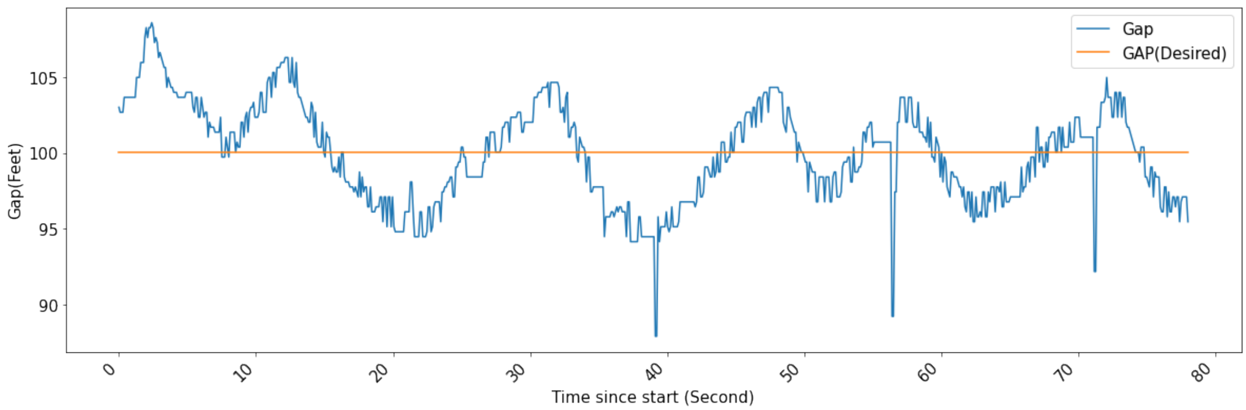

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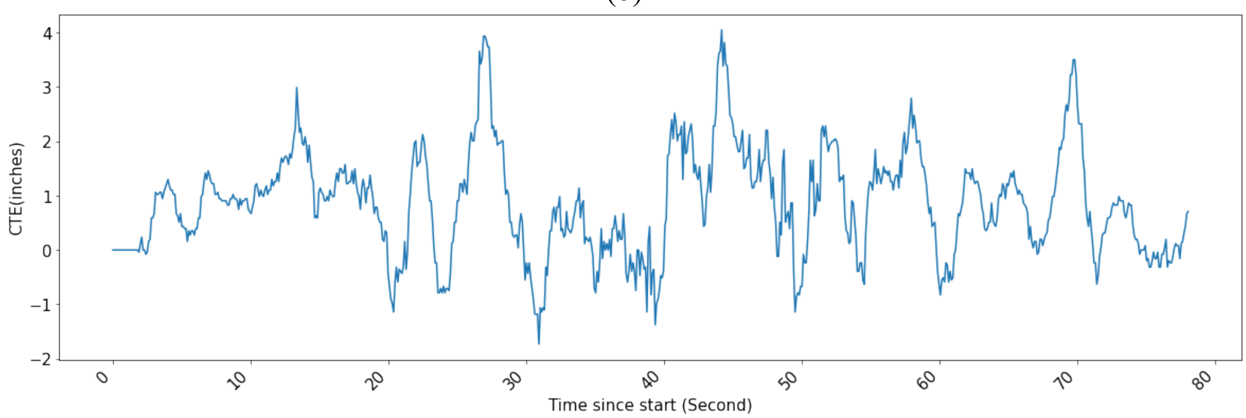
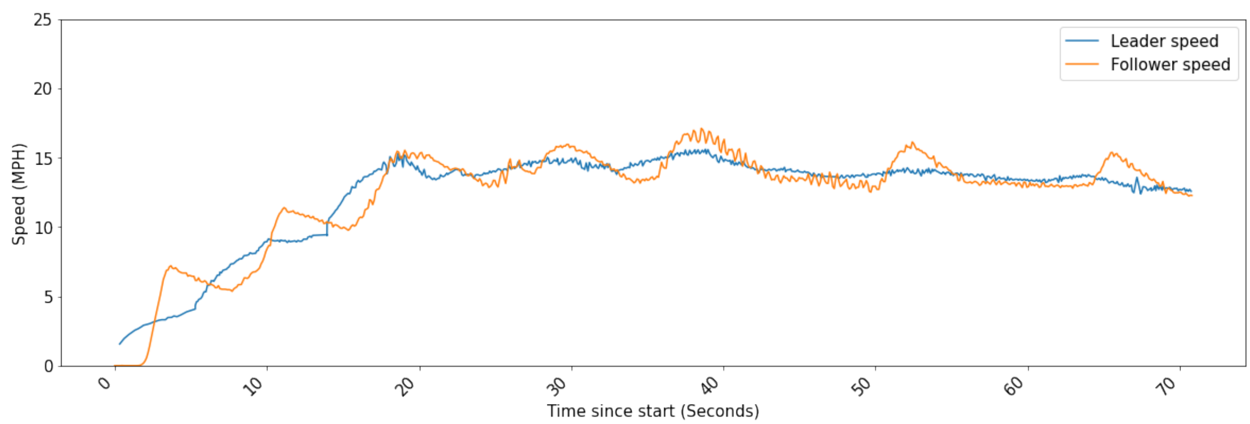


(c)

Figure B.50 Test case 9, Run 12: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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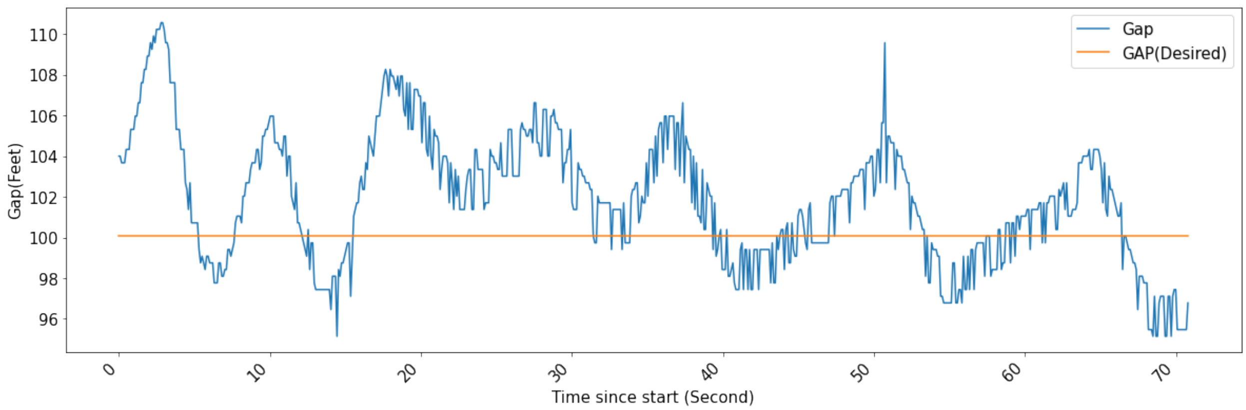
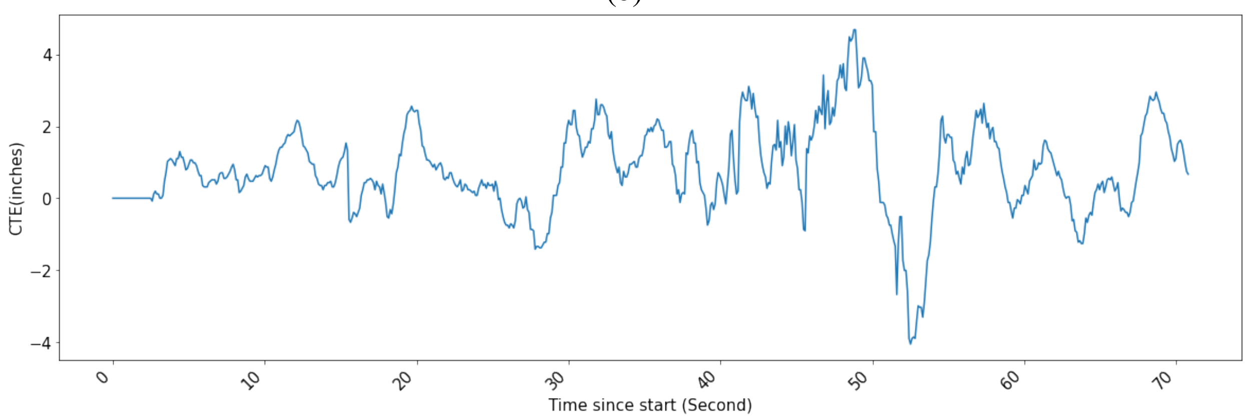
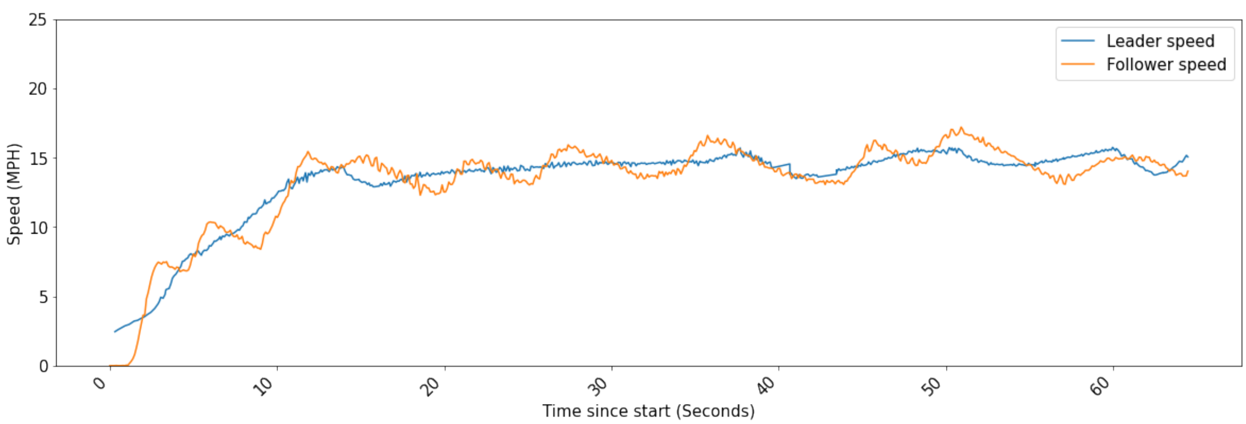


(b)

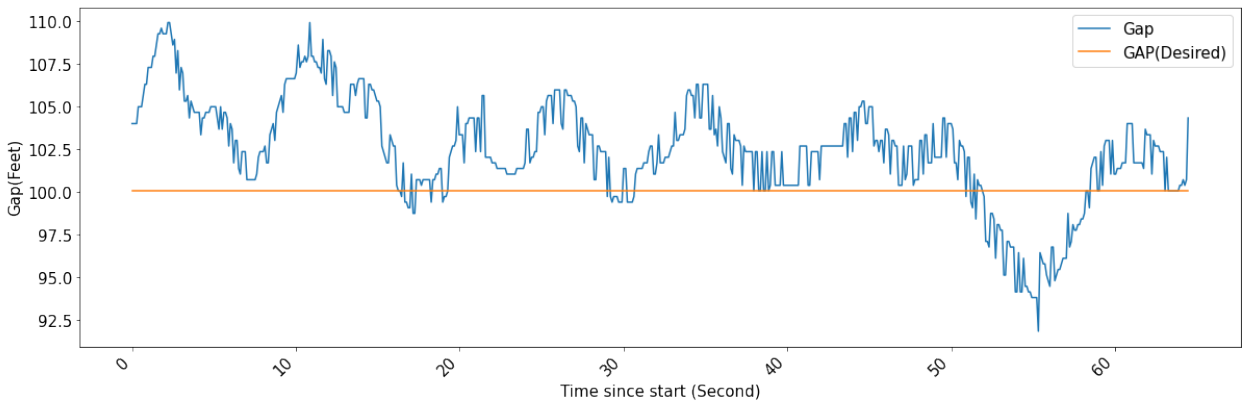


(c)

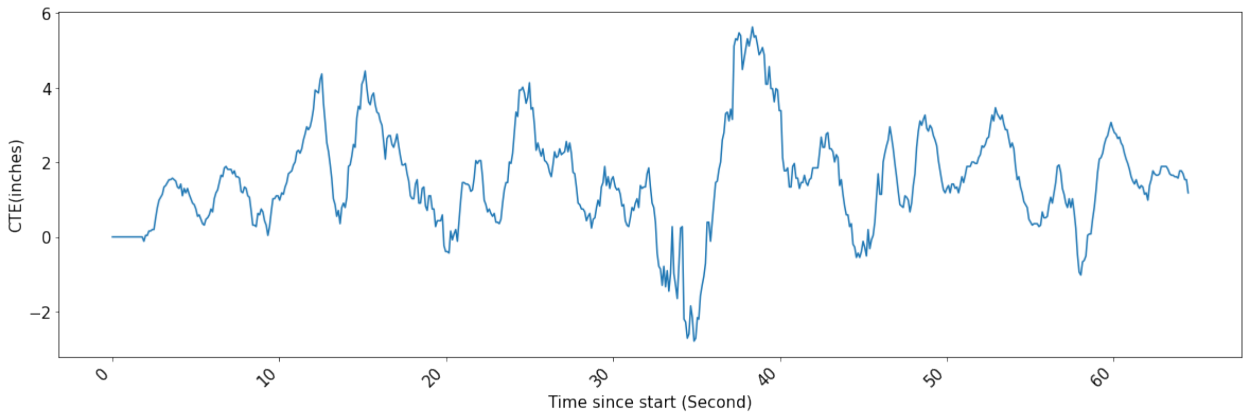
Figure B.51 Test case 9, Run 13: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



(a)

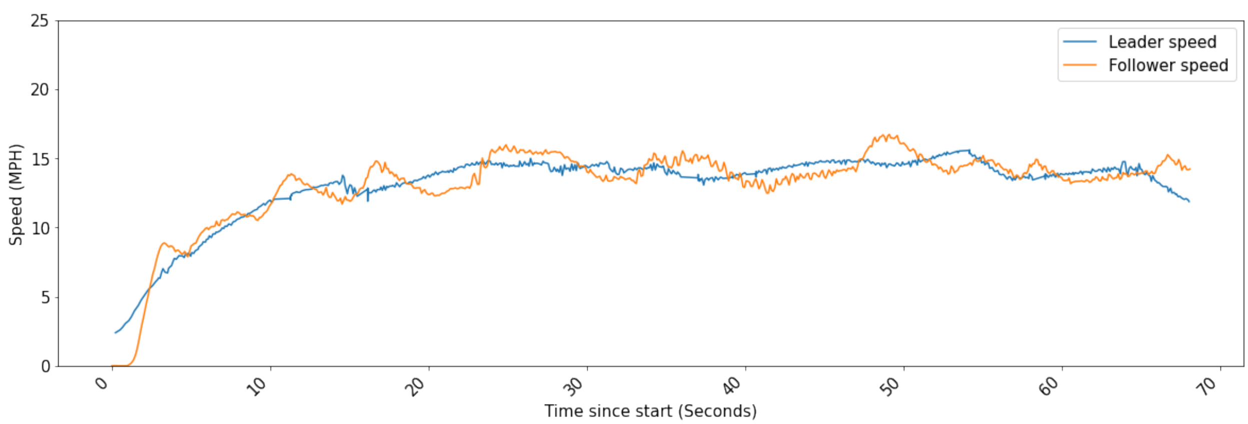


(b)

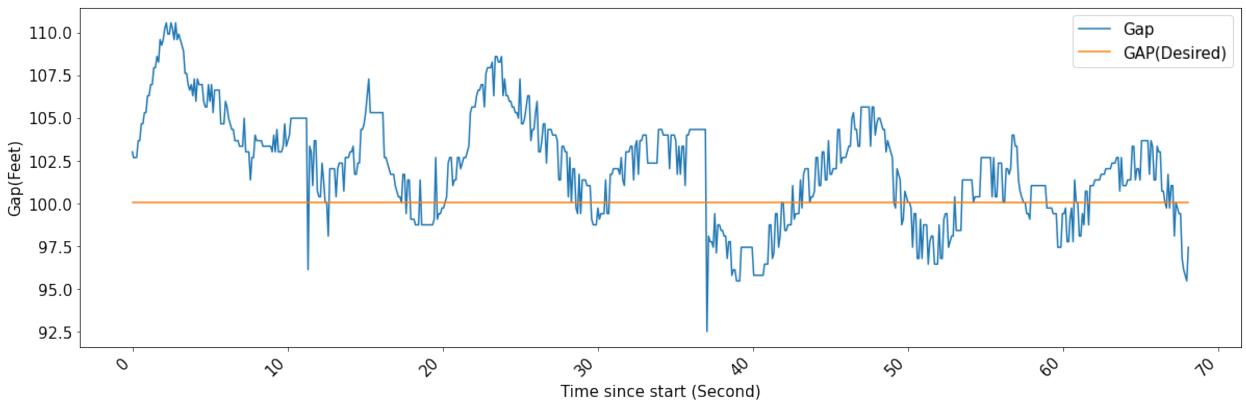


(c)

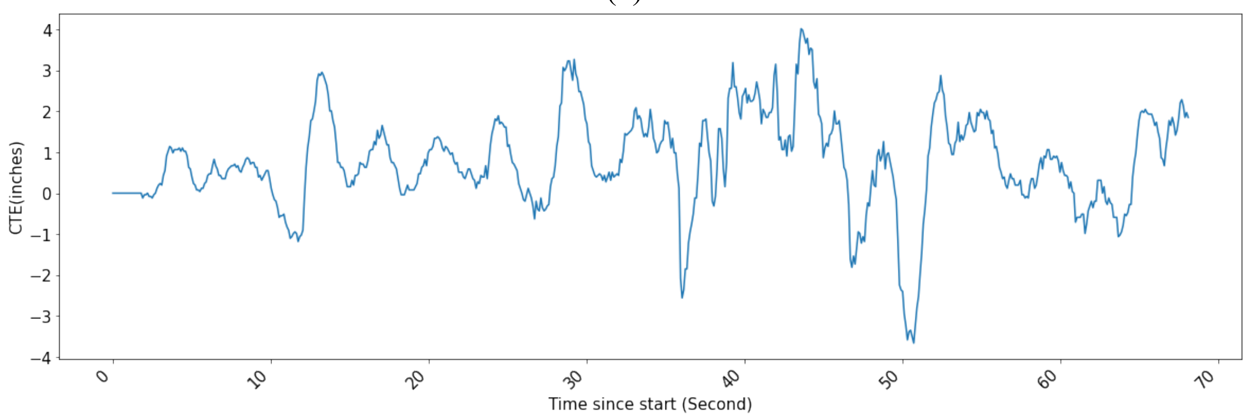
Figure B.52 Test case 9, Run 14: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



(a)

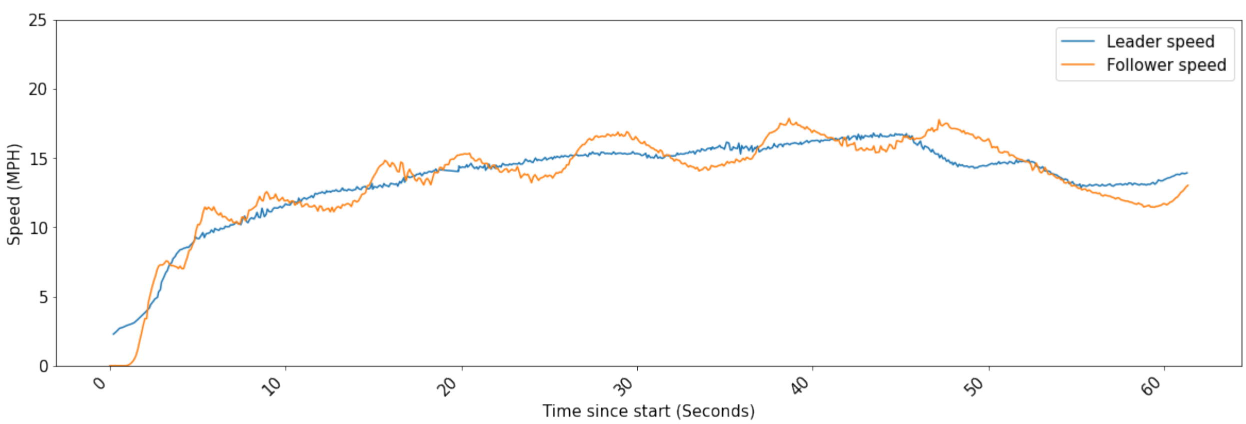


(b)

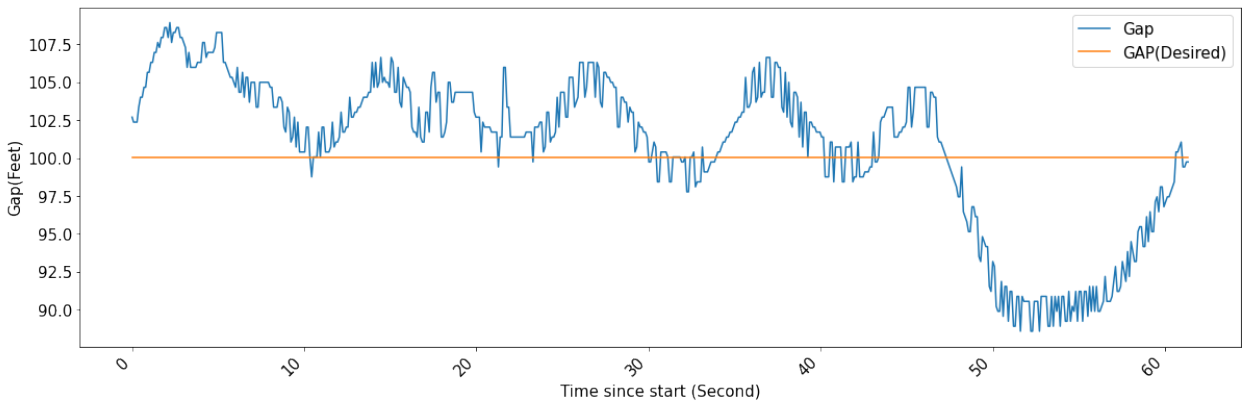


(c)

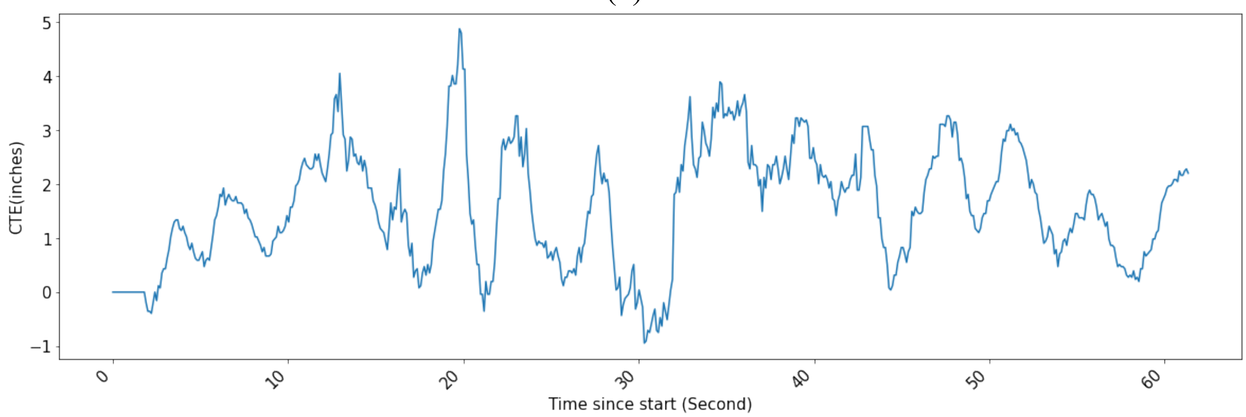
Figure B.53 Test case 9, Run 15: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



(a)

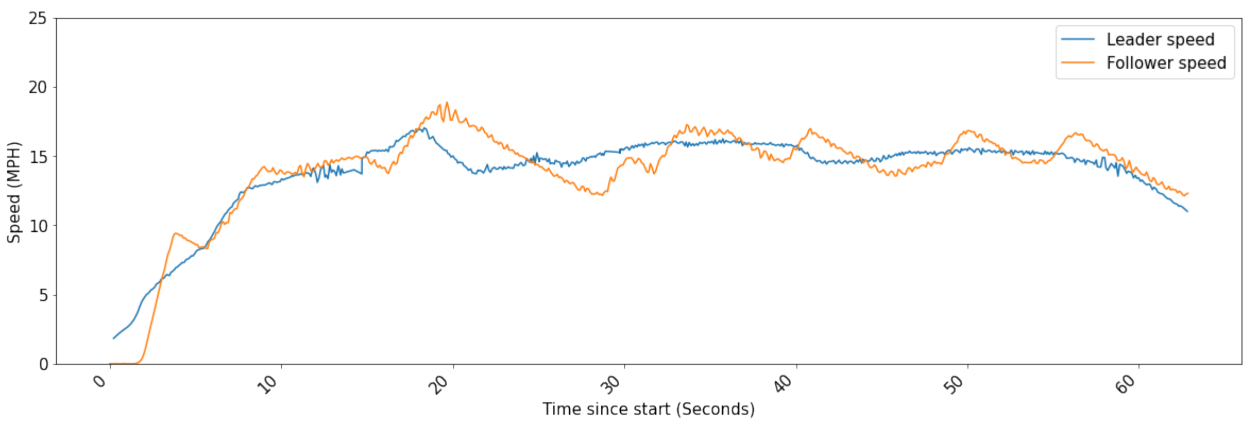


(b)

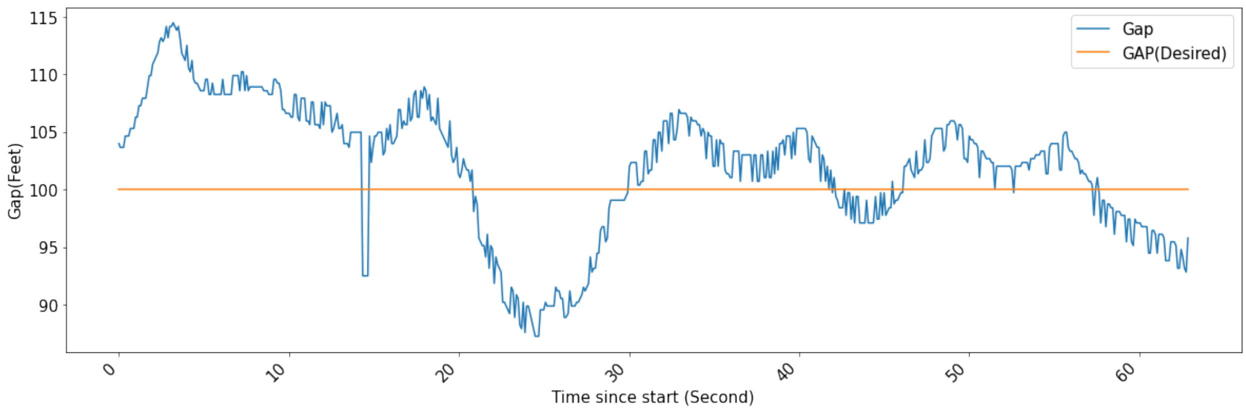


(c)

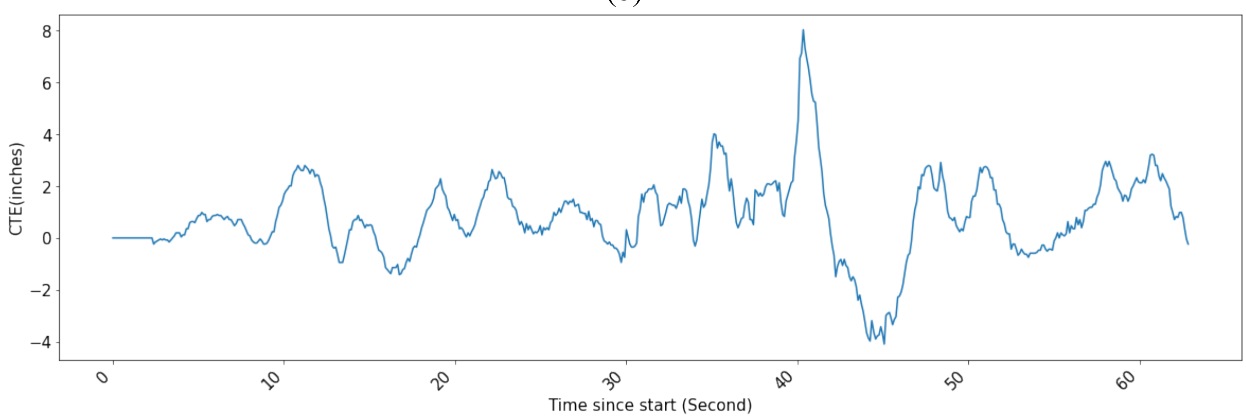
Figure B.54 Test case 9, Run 16: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



(a)

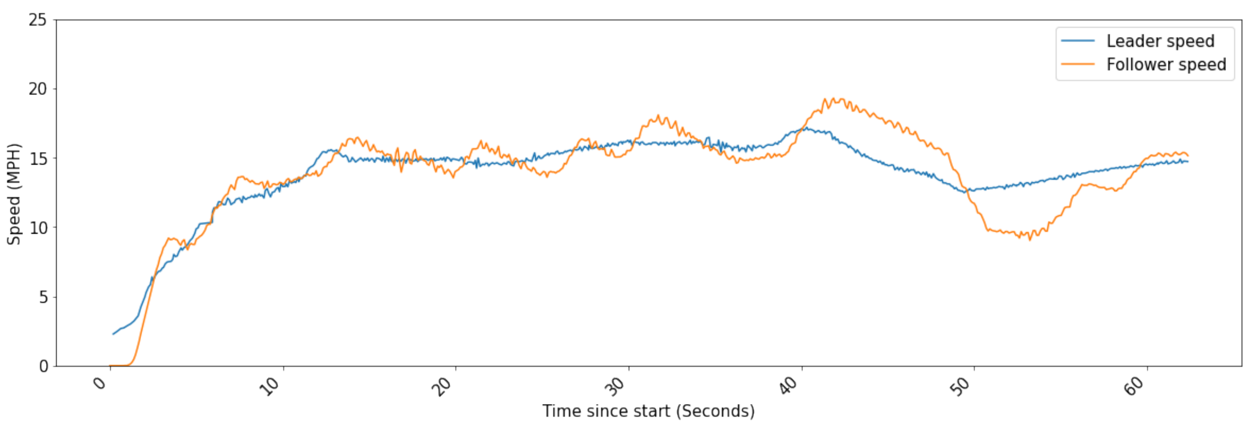


(b)

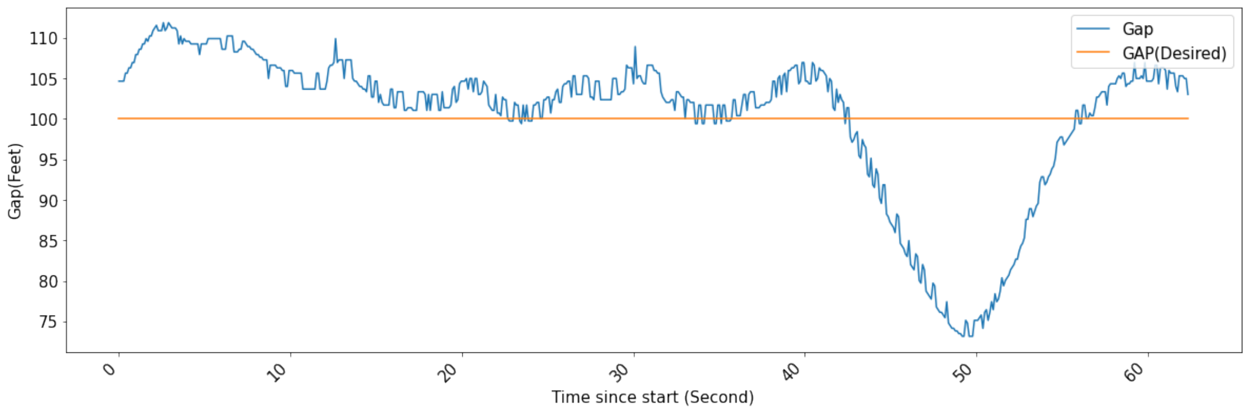


(c)

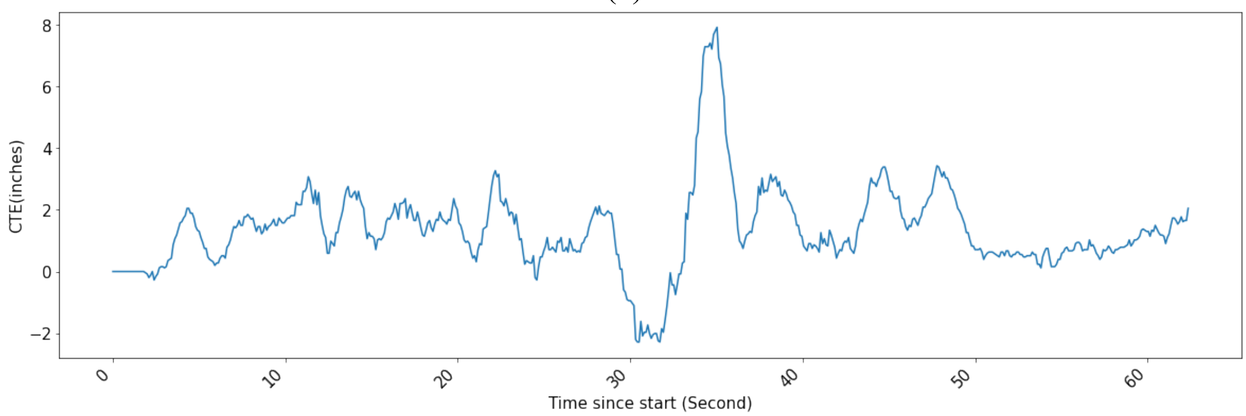
Figure B.55 Test case 9, Run 17: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



(a)



(b)



(c)

Figure B.56 Test case 9, Run 18: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.

Test Case 10: Lateral Offset

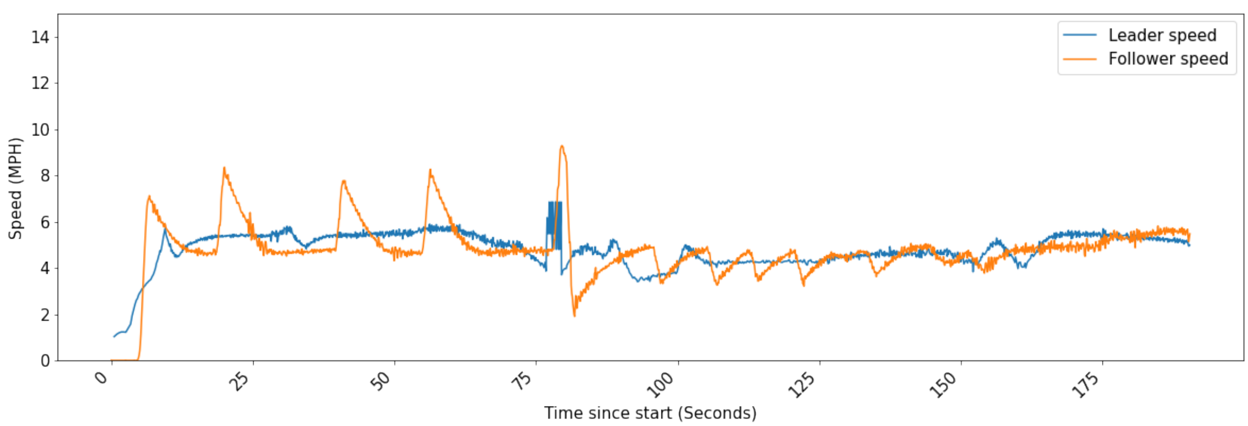
Table B.24 Test Procedure-Test Case 10

Operation procedure	• Activate the leader and ATMA and set the gap to 100 feet and drive in a straight line at 5 mph. • While traveling at a steady speed of 5mph, set ATMA lateral offset to 1 foot, 5 feet, 12 feet, 5 feet, and 1 foot. • Repeat the test at the speed of 10 mph and 15 mph.
Data collection	• Measure the time taken to stabilize the offset. • Collect ATMA offset measurements.
Expected results	The ATMA can perform the lateral offset.
Total number of runs	3 runs (Each run has six subtasks.)
Supporting equipment	Walkie-talkie, Traffic cones
Supporting staff from INDOT	Leader vehicle driver, ATMA driver, ATMA operator in leader vehicle

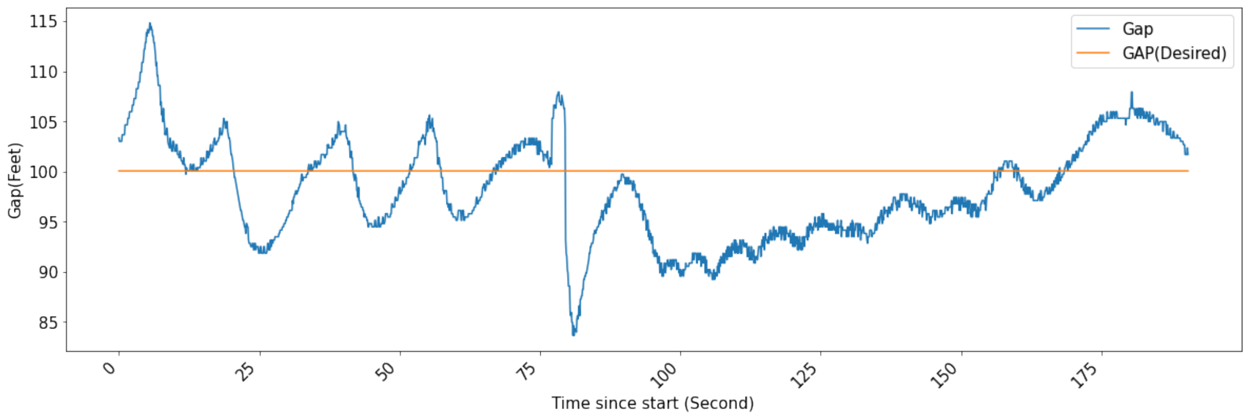
All three runs were performed successfully. Table B.25 shows the actual lateral offsets and time to stabilization. Figure B.57to Figure B.59 show leader truck speed vs. follower truck speed, gap vs. desired gap, CTE, and actual lateral offsets vs. commanded lateral offsets for each run.

Table B.25 Data Collection Form-Test Case 10

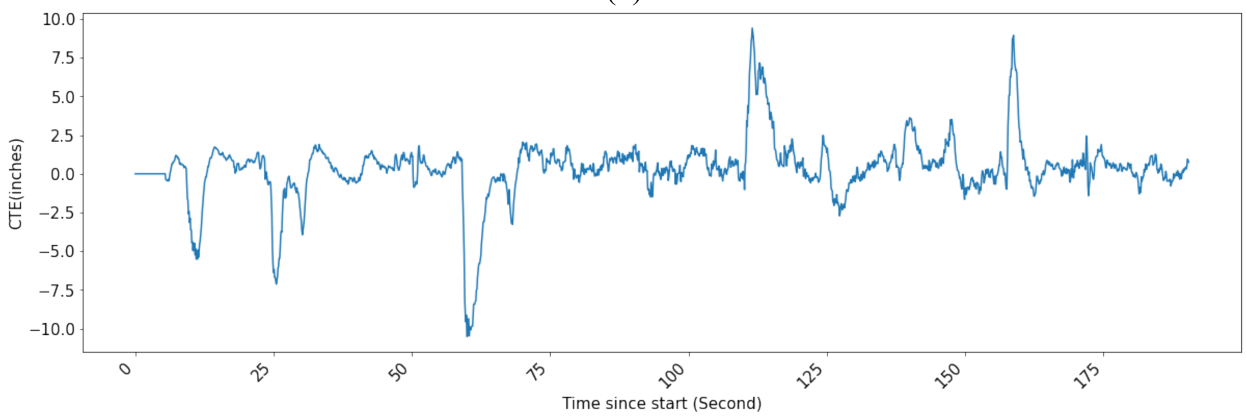
Runs	Speed	Lateral offsets	Actual lateral offsets	Time to stabilization (Seconds)
1a	5 mph	0 → 1	1	00:00:02.22
1b	5 mph	1 → 5	5	00:00:05.54
1c	5 mph	5 → 12	12	00:00:08.89
1d	5 mph	12 → 5	5	00:00:14.22
1e	5 mph	5 → 1	1	00:00:08.73
1f	10 mph	1 → 0	0	00:00:01.01
2a	10 mph	0 → 1	1	00:00:00.39
2b	10 mph	1 → 5	5	00:00:05.37
2c	10 mph	5 → 12	12	00:00:07.12
2d	10 mph	12 → 5	5	00:00:09.24
2e	10 mph	5 → 1	1	00:00:05.28
2f	10 mph	1 → 0	0	00:00:00.83
3a	15 mph	0 → 1	1	00:00:00.27
3b	15 mph	1 → 5	5	00:00:05.47
3c	15 mph	5 → 12	12	00:00:08.20
3d	15 mph	12 → 5	5	00:00:09.08
3e	15 mph	5 → 1	1	00:00:05.64
3f	15 mph	1 → 0	0	00:00:01.91



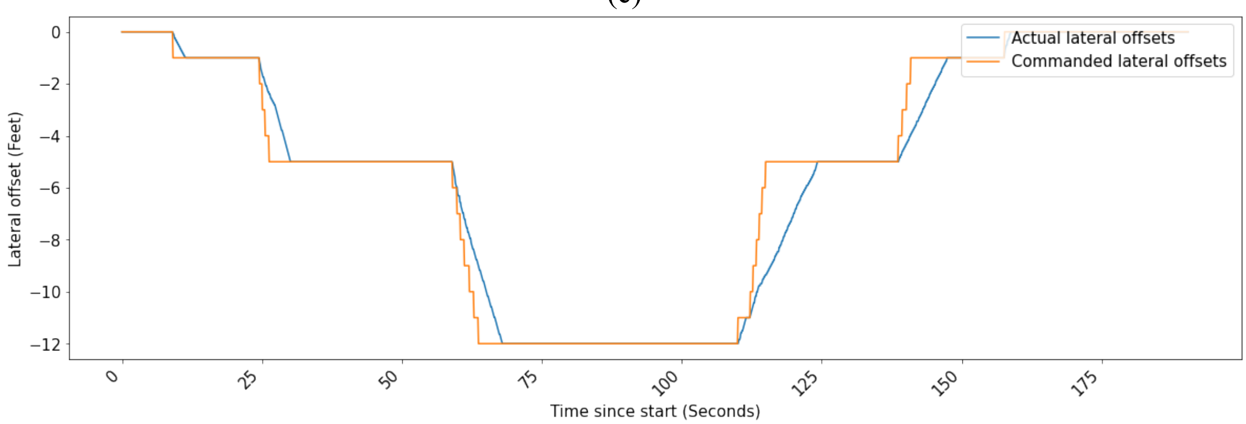
(a)



(b)

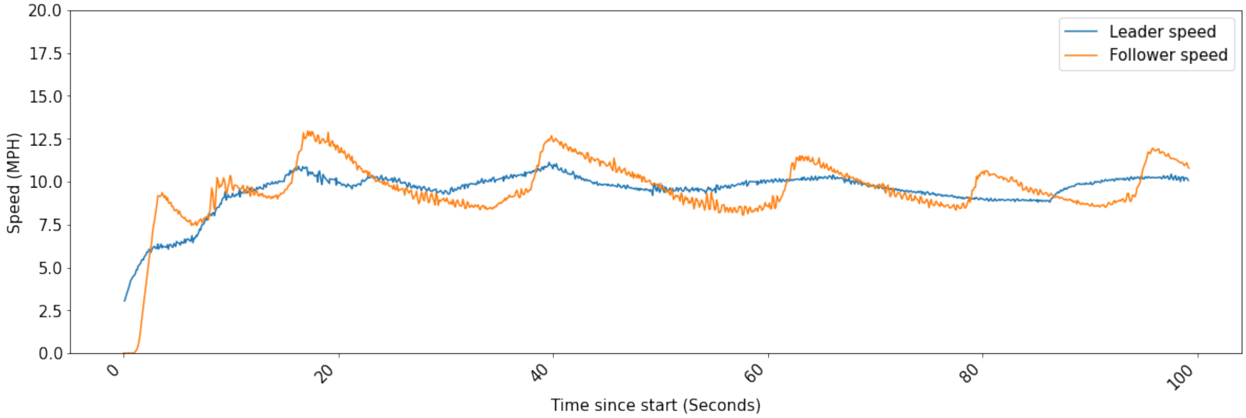


(c)

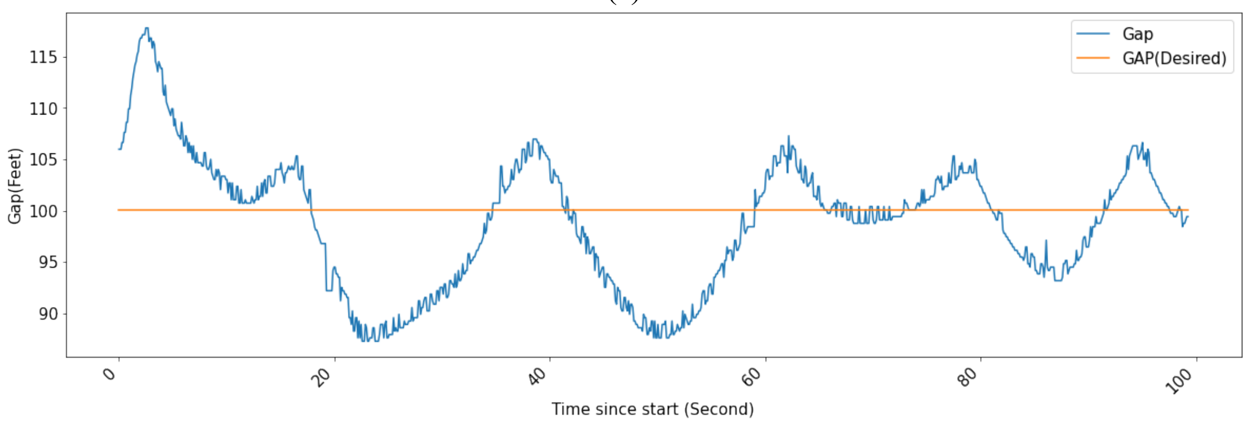


(d)

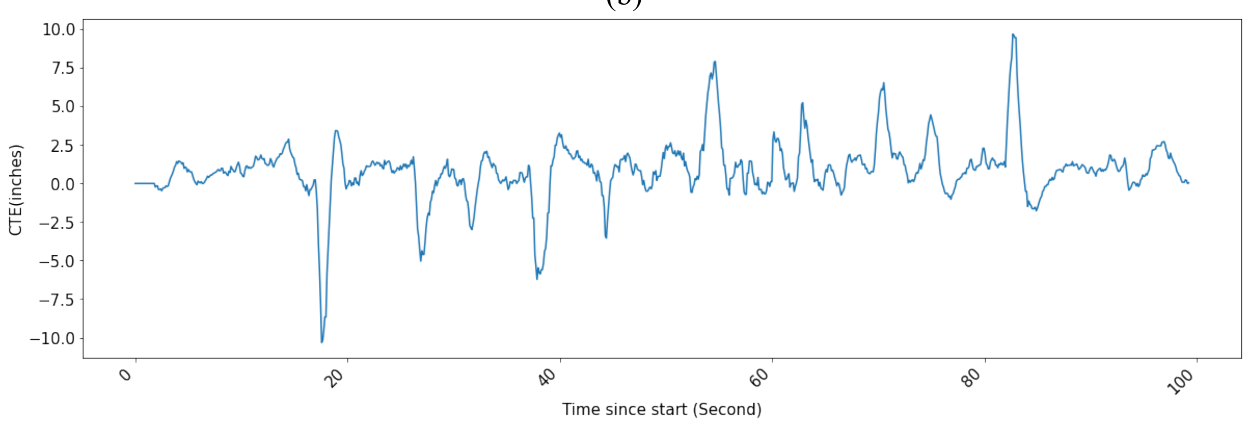
Figure B.57 Test case 10, Run 1: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE, (d) actual lateral offsets vs. commanded lateral offsets.


20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
Speed (MPH)
Leader speed
Follower speed
0
20
40
60
80
100
Time since start (Seconds)

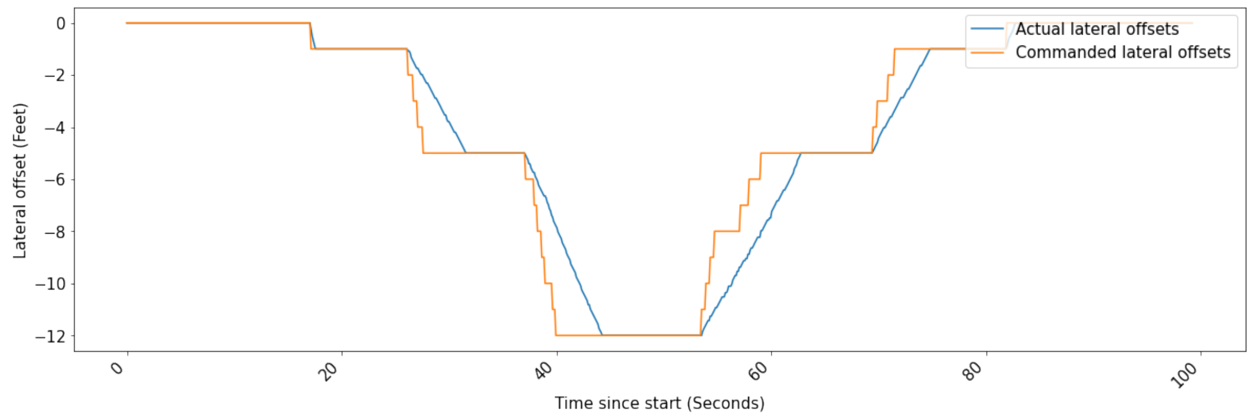
(a)


115
110
105
100
95
90
Gap(Feet)
Gap
GAP(Desired)
0
20
40
60
80
100
Time since start (Second)

(b)

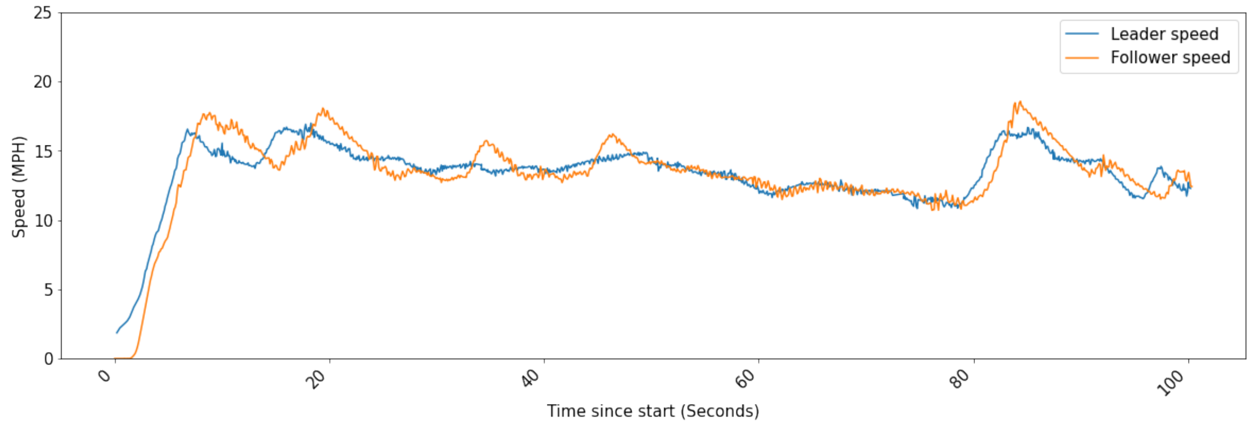

10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
CTE(inches)
0
20
40
60
80
100
Time since start (Second)

(c)

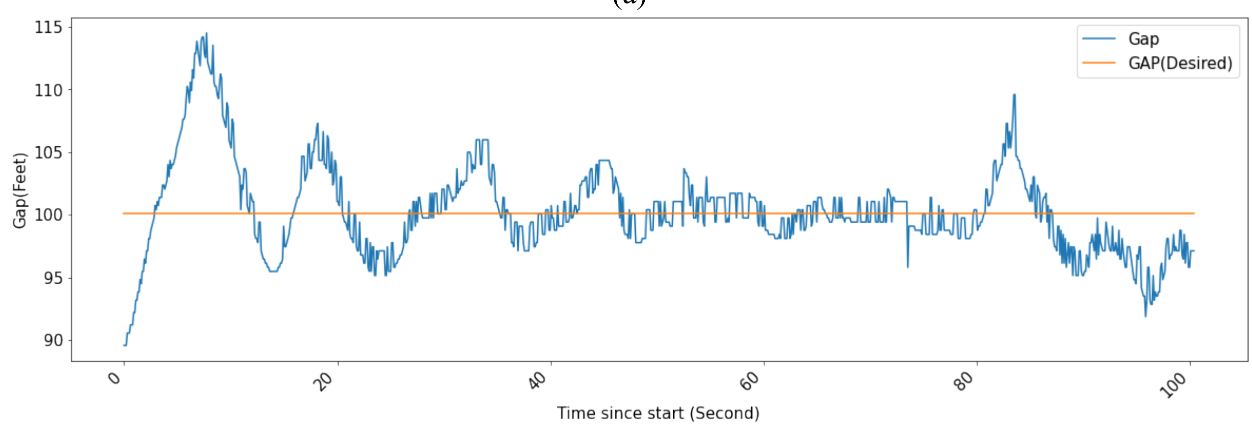


(d)

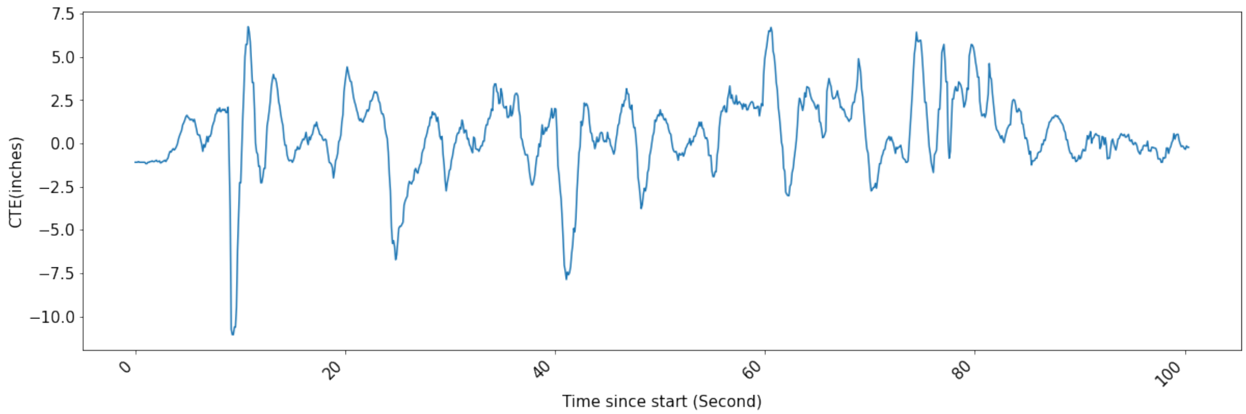
Figure B.58 Test case 10, Run 2: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE, and (d) actual lateral offsets vs. commanded lateral offsets.



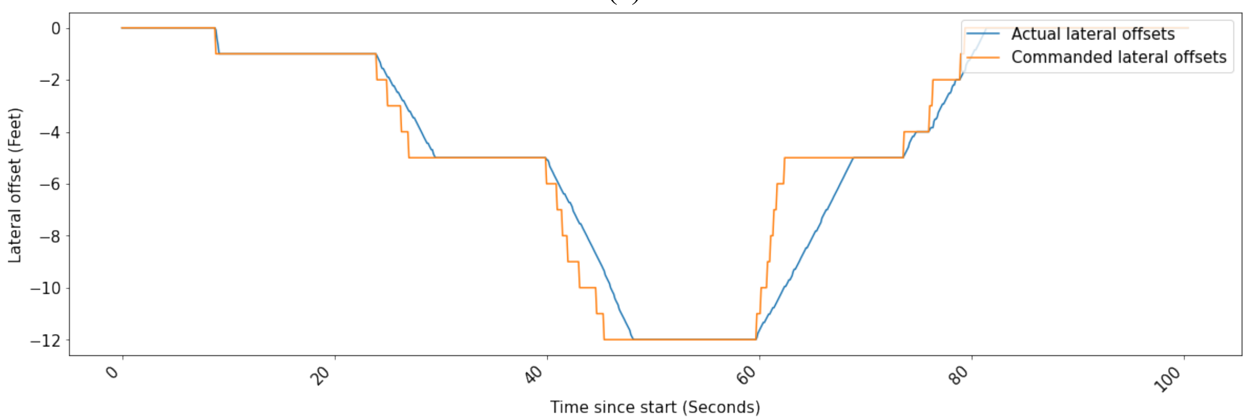
(a)



(b)



(c)



(d)

Figure B.59 Test case 10, Run 3: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE, and (d) actual lateral offsets vs. commanded lateral offsets.

B.4 Focus Area 4: Turning Capacity

Test Case 11: Minimum Turning Radius

Table B.26 Test Procedure-Test Case 11

Operation procedure	• Set up a 90° corner with cones spaced at an interval of 50 feet and an internal turn radius of 45 feet. • Activated the leader and ATMA and drive in a straight line at 5 mph. • Repeated for left and right turns. • Conducted 3 runs for each radius. • Repeated with 35 feet, and 25 feet until the ATMA cannot perform the turn.
Data collection	• Collected ATMA log files
Expected results	The ATMA can turn successfully.
Total number of runs	18 runs
Supporting equipment	Walkie-talkie, Traffic cones
Supporting staff from INDOT	Leader vehicle driver, ATMA driver, ATMA operator in leader vehicle

Figure B.60 displays the layout of the minimum turning radius test.

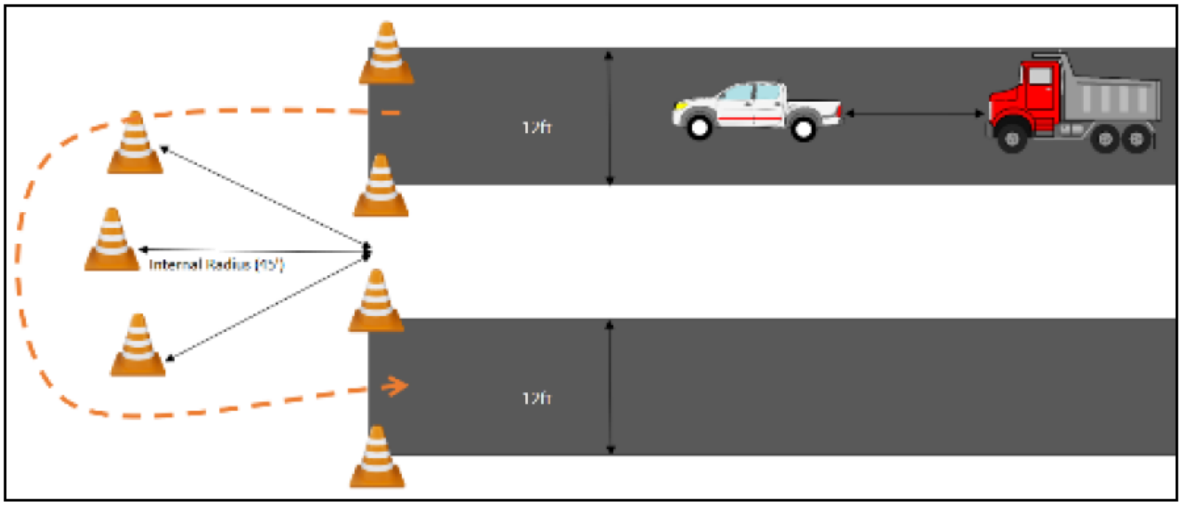


Figure B.60 The Layout of Minimum Radius Setup (Agarwal et al., 2021).

The ATMA system turned successfully for both left and right for 45 feet and 35 feet as shown in Table B.27. The ATMA system turned successfully for a left turn with a 25 feet radius. However, the ATMA cannot make a right turn with a 25 feet radius. The error was an Ecrumb error which caused A-stop.

Table B.27 Data Collection Form-Test Case 11

Runs	Test Speed	Internal turn radius	Turning direction	Yes / No
1	5 mph	45 feet	Left	Yes
2	5 mph	45 feet	Left	Yes
3	5 mph	45 feet	Left	Yes
4	5 mph	45 feet	Right	Yes
5	5 mph	45 feet	Right	Yes
6	5 mph	45 feet	Right	Yes
7	5 mph	35 feet	Left	Yes
8	5 mph	35 feet	Left	Yes
9	5 mph	35 feet	Left	Yes
10	5 mph	35 feet	Right	Yes
11	5 mph	35 feet	Right	Yes
12	5 mph	35 feet	Right	Yes
13	5 mph	25 feet	Left	Yes
14	5 mph	25 feet	Left	Yes
15	5 mph	25 feet	Left	Yes
16	5 mph	25 feet	Right	No
17	5 mph	25 feet	Right	No
18	5 mph	25 feet	Right	No

Test Case 12: Curve

Table B.28 Test Procedure-Test Case 12

Operation procedure	• Activated the leader truck and ATMA and drive at 5 mph. • Repeated with 10 mph and 15 mph. • Conducted 3 runs for each speed.
Data collection	• Collected ATMA lateral accuracy.
Expected results	The ATMA maintains a lateral accuracy of ±6 inches when passing the curves.
Total number of runs	9 runs
Supporting equipment	Walkie-talkie
Supporting staff from INDOT	Leader vehicle driver, ATMA driver, ATMA operator in leader vehicle

The location of the curve (highlighted in red rectangle) at the Indianapolis office is shown in Figure B.61. All 9 runs were performed successfully. However, the GPS was forced into DR mode several times, between 9.26 AM–10:06 AM, and 11:20 AM–11:40 AM. The ATMA system cannot be operated automatically in DR mode. The issues were solved by restarting the ATMA system.

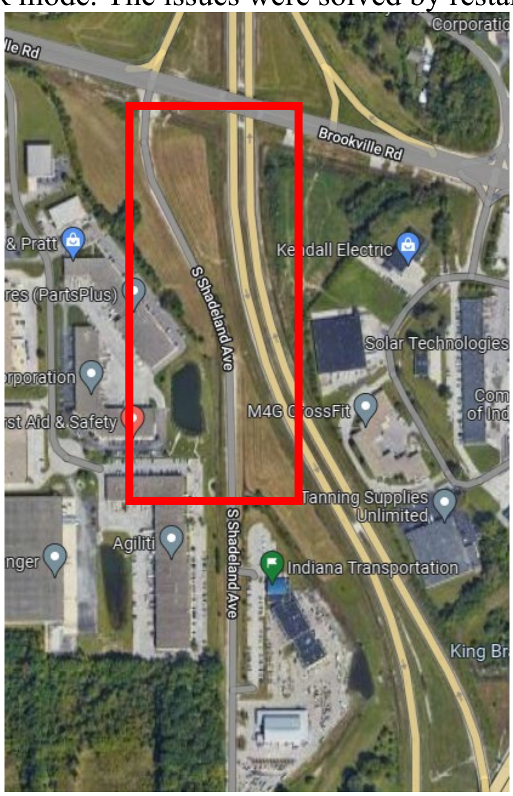


Figure B.61 Curve Location at Indianapolis Unit.

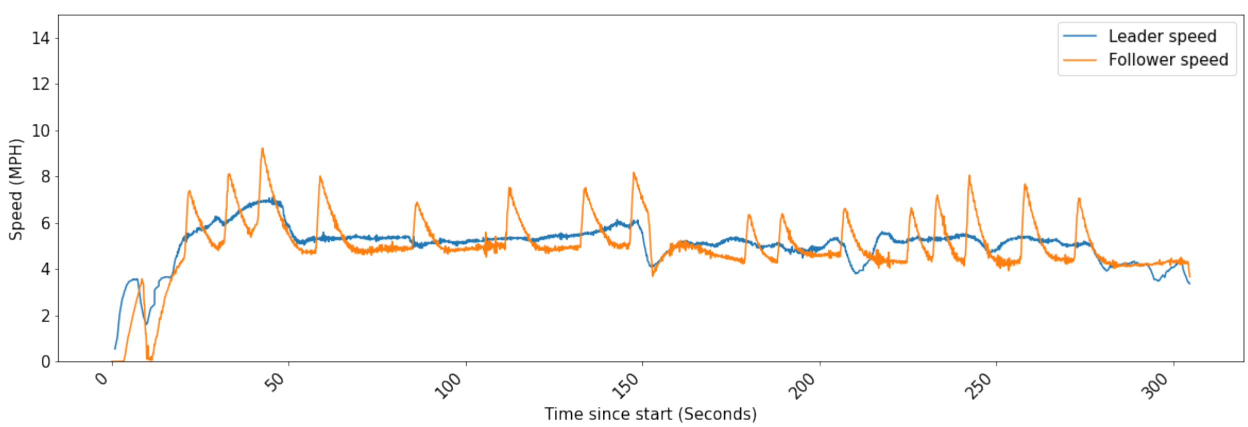
Table B.29 and Table B.30 show the gap difference and CTE for each run. Runs 4, 5, 7, 8, and 9 did not meet the CTE requirements of the ATMA system. Figure B.62 to Figure B.70 show leader truck speed vs. follower truck speed, gap vs. the desired gap, and CTE for each run.

Table B.29 Gap difference for each run – case 12

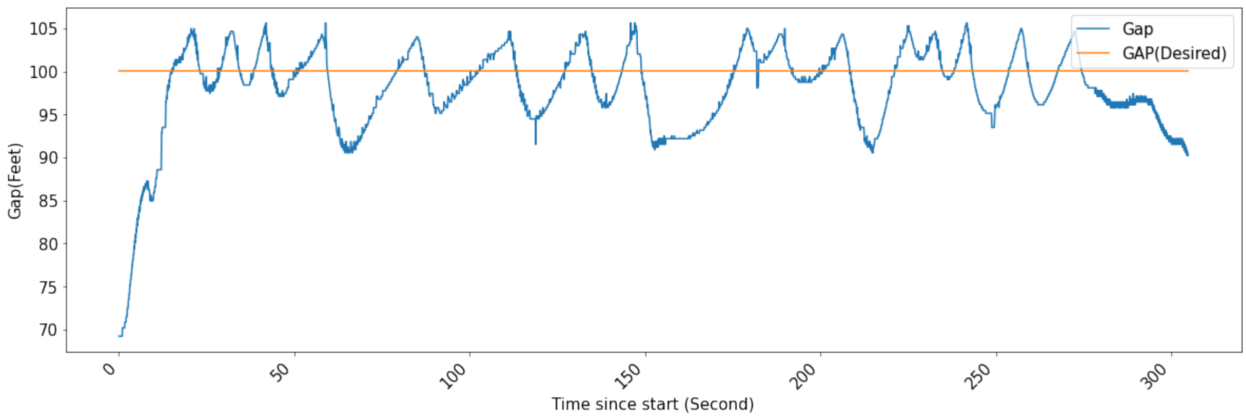
Runs	Test Speed	Gap Difference (feet)			
		Max	Min	Mean	Std.
1	5 mph	5.577	-30.840	-2.124	5.254
2	5 mph	6.234	-24.606	-1.849	4.456
3	5 mph	6.562	-79.0682	-2.700	10.817
4	10 mph	6.234	-36.089	-2.557	6.624
5	10 mph	6.890	-77.0997	-2.665	13.254
6	10 mph	7.218	-82.677	-3.00352	12.838
7	15 mph	23.950	-90.223	-1.867	21.206
8	15 mph	14.437	-92.847	-2.0344	18.475
9	15 mph	11.155	-30.512	0.632	4.872

Table B.30 CTE – case 12

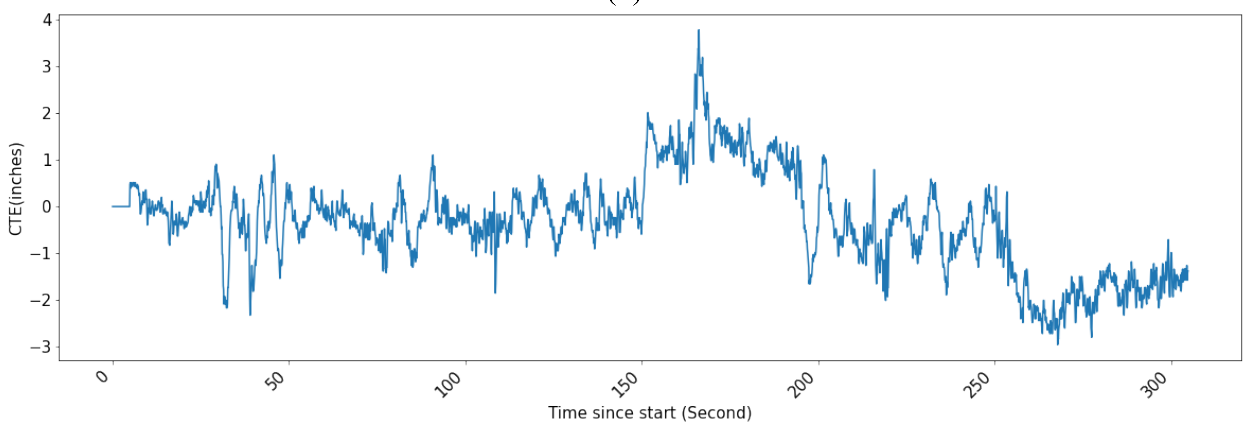
Runs	Test Speed	CTE (Inches)			
		Max	Min	Mean	Std.
1	5 mph	3.780	-2.953	-0.326	1.021
2	5 mph	2.756	-3.189	-0.467	0.989
3	5 mph	2.913	-2.795	-0.402	0.948
4	10 mph	9.882	-1.496	1.842	1.701
5	10 mph	6.654	-1.772	1.716	1.514
6	10 mph	5.866	-1.535	1.692	1.431
7	15 mph	10.315	-1.572	2.395	2.272
8	15 mph	9.764	-2.0866	2.791	2.386
9	15 mph	5.315	-6.654	-1.0900	2.217



(a)

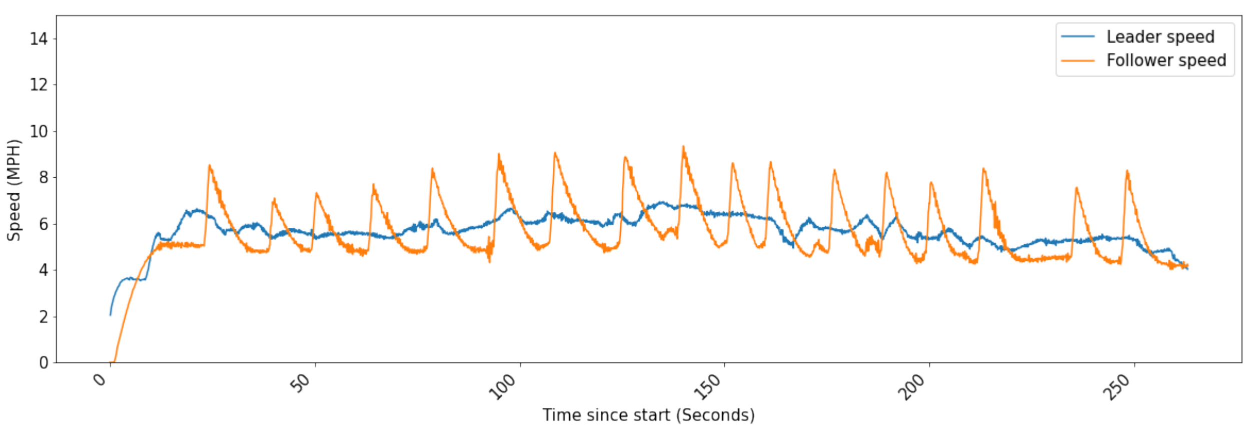


(b)

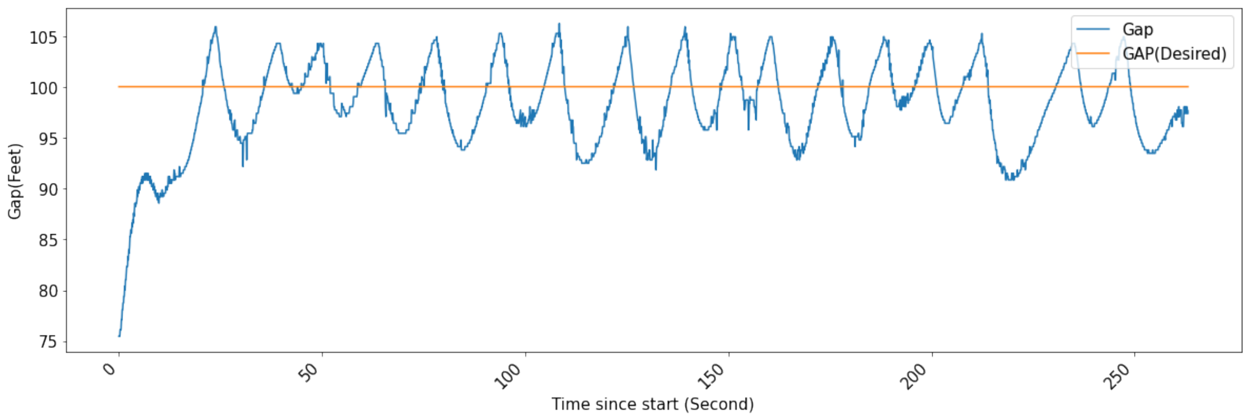


(c)

Figure B.62 Test case 12, Run 1: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



(a)



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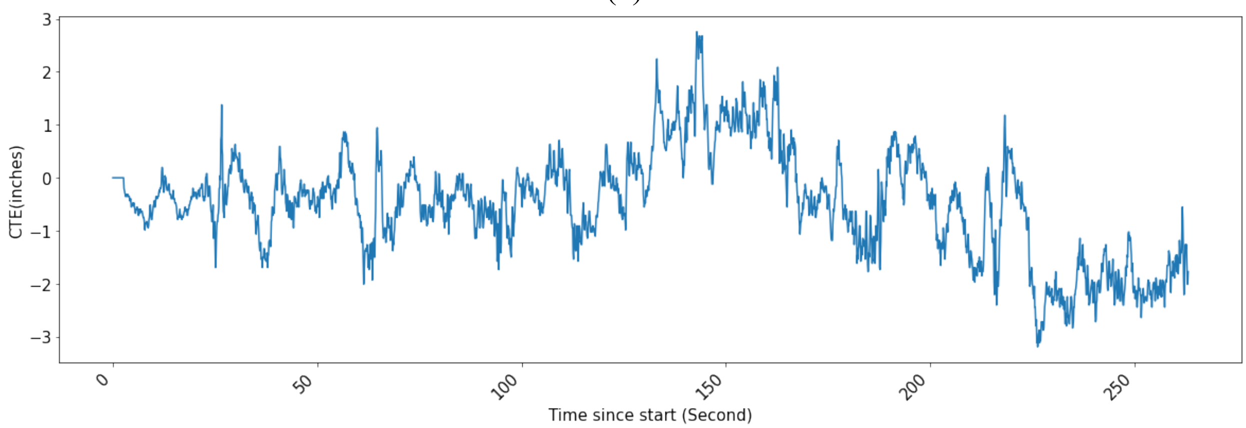
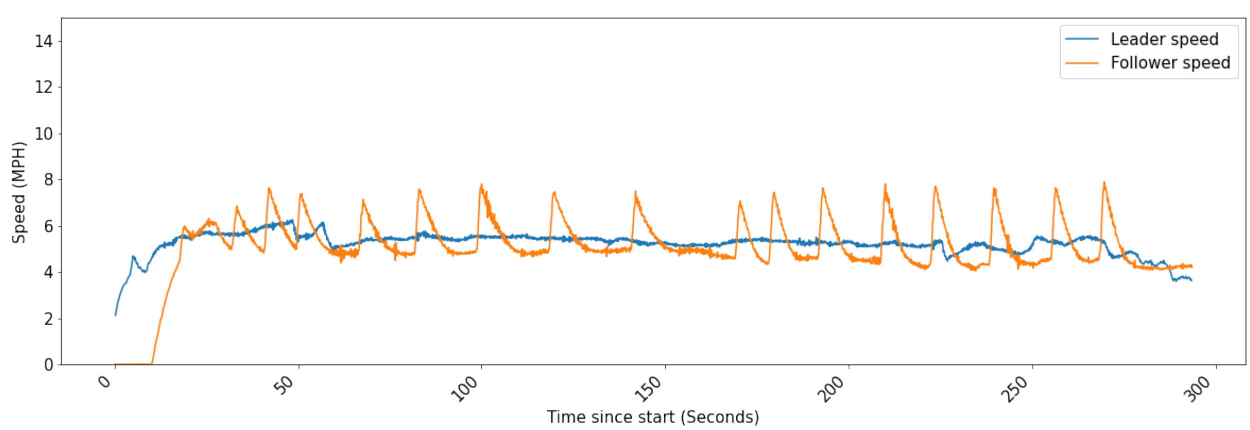
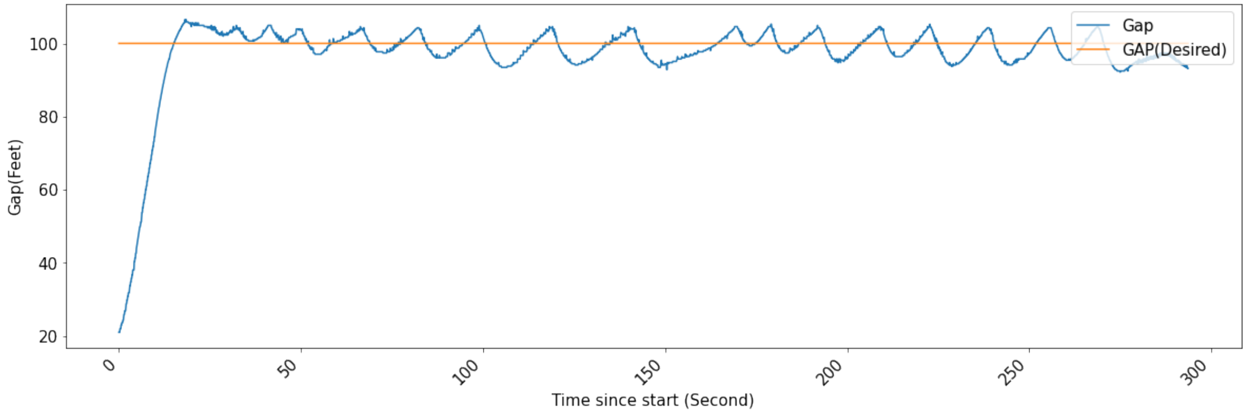


(c)

Figure B.63 Test case 12, Run 2: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



(a)



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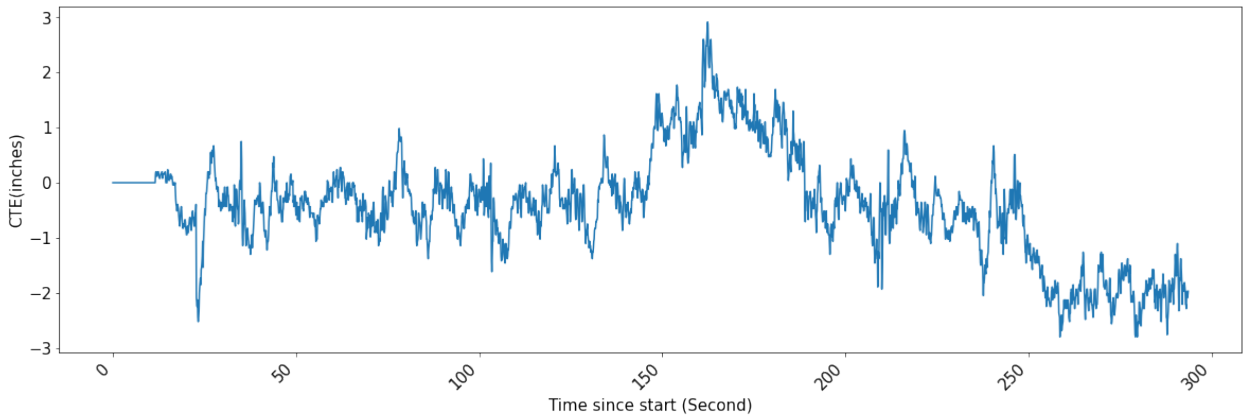
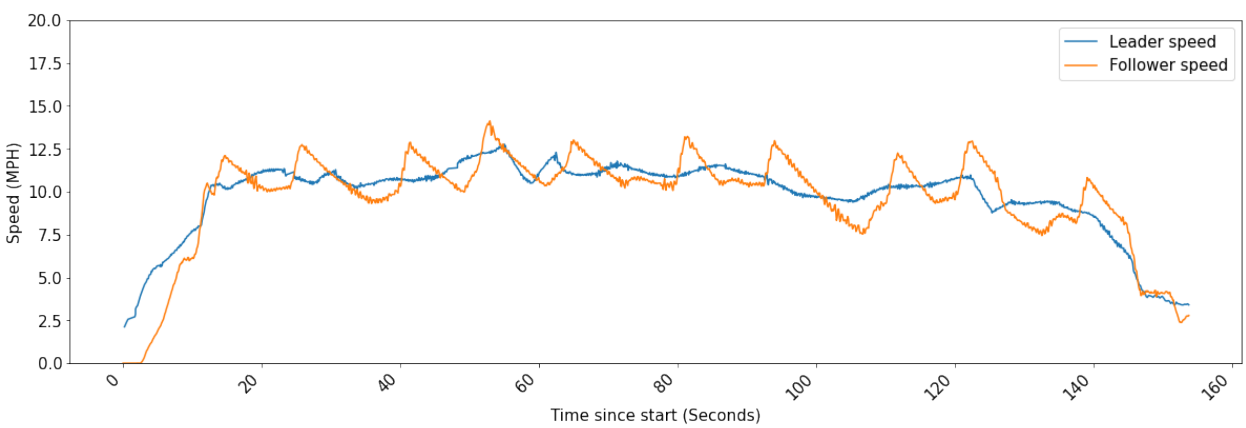
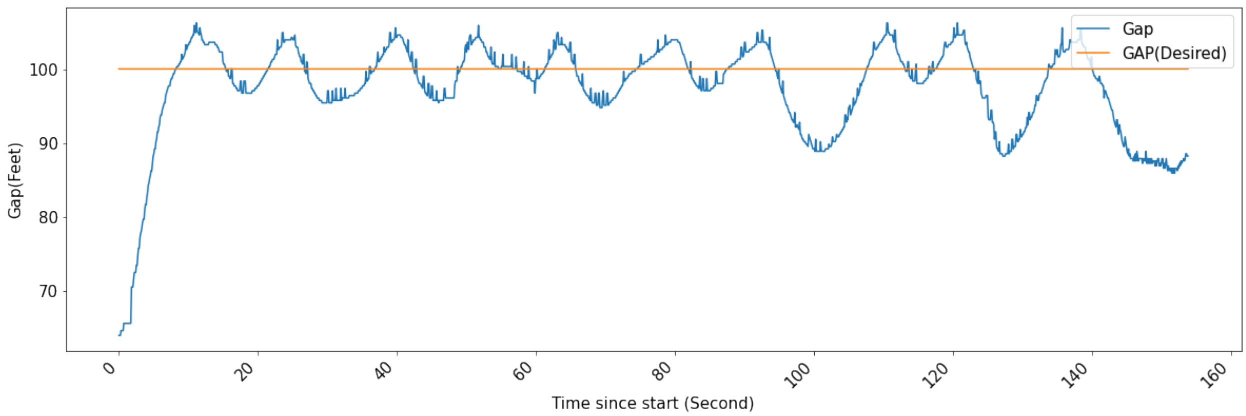


(c)

Figure B.64 Test case 12, Run 3: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.



(a)



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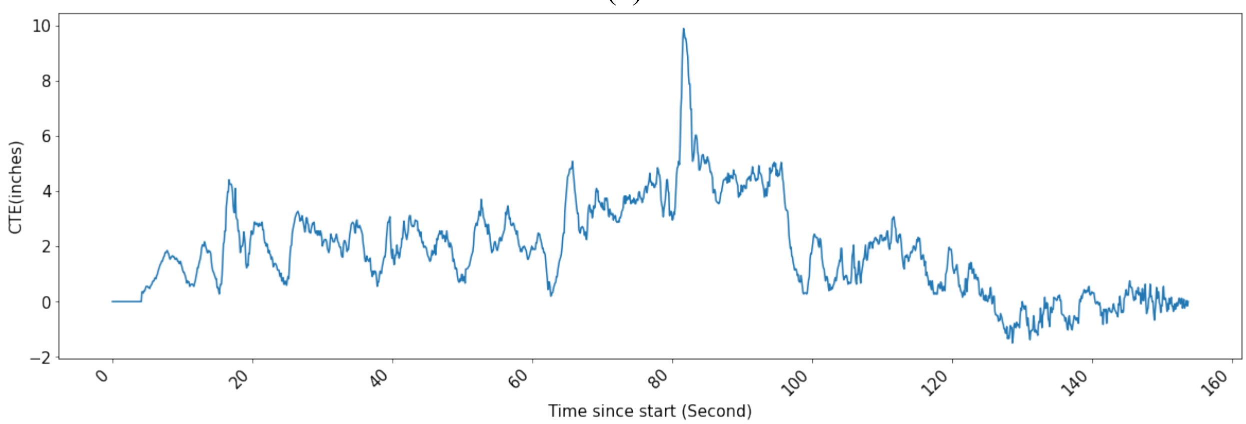
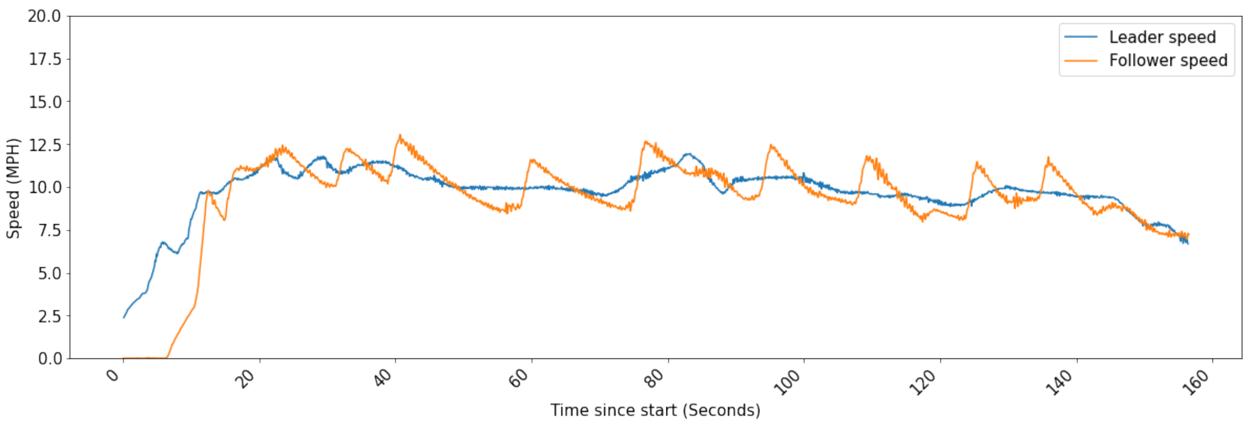
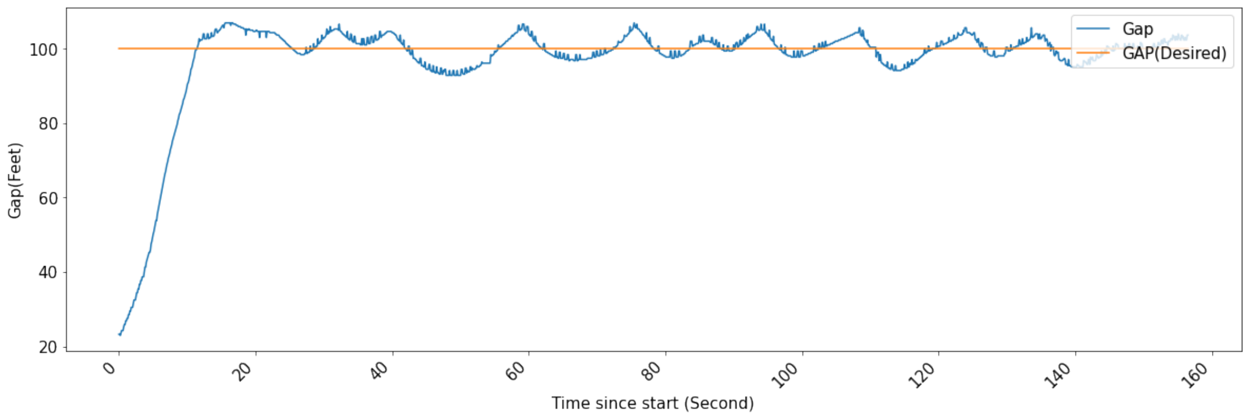


(c)

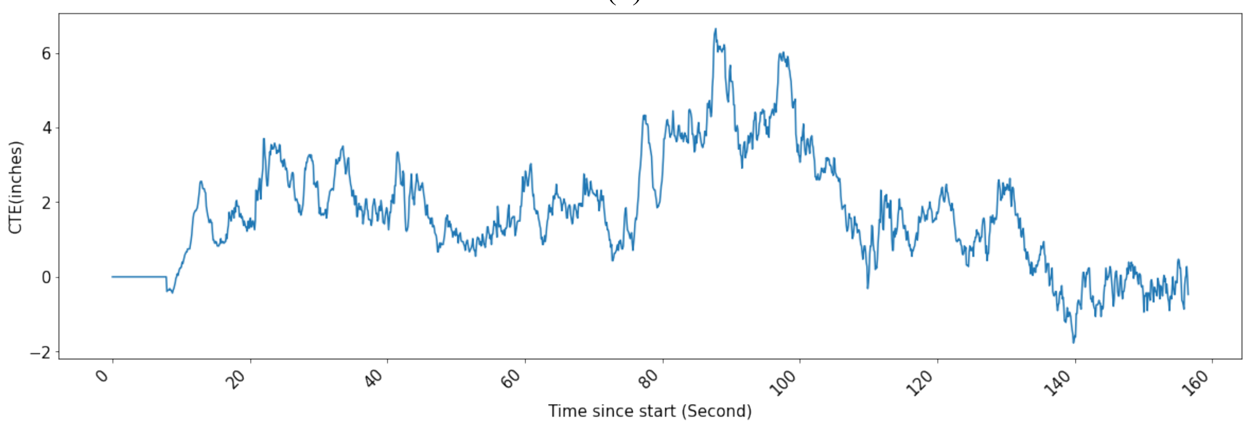
Figure B.65 Test case 12, Run 4: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.



(a)

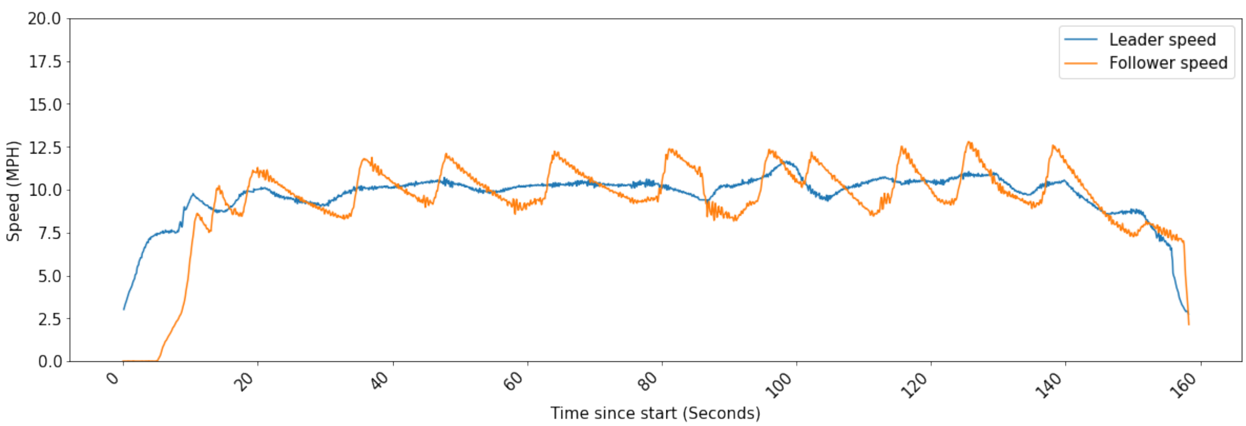


(b)

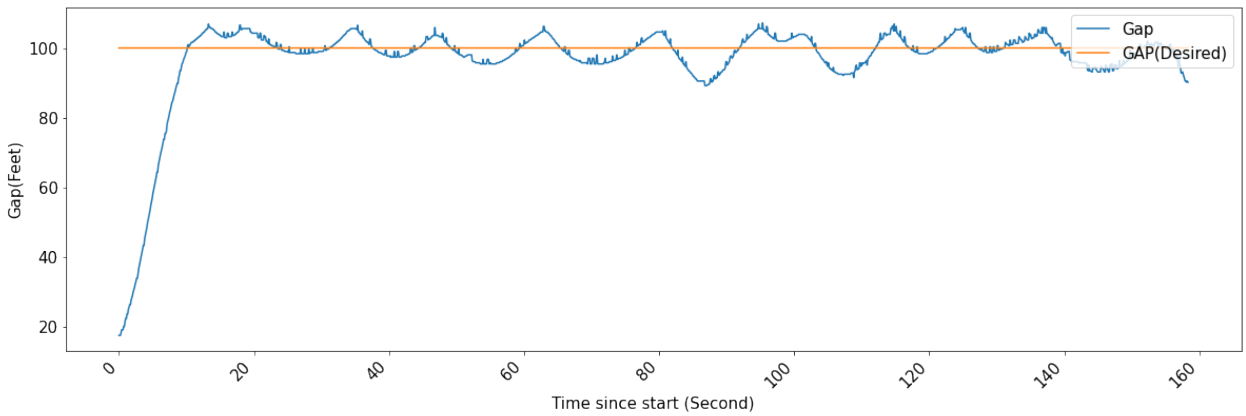


(c)

Figure B.66 Test case 12, Run 5: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, and (c) CTE.



(a)



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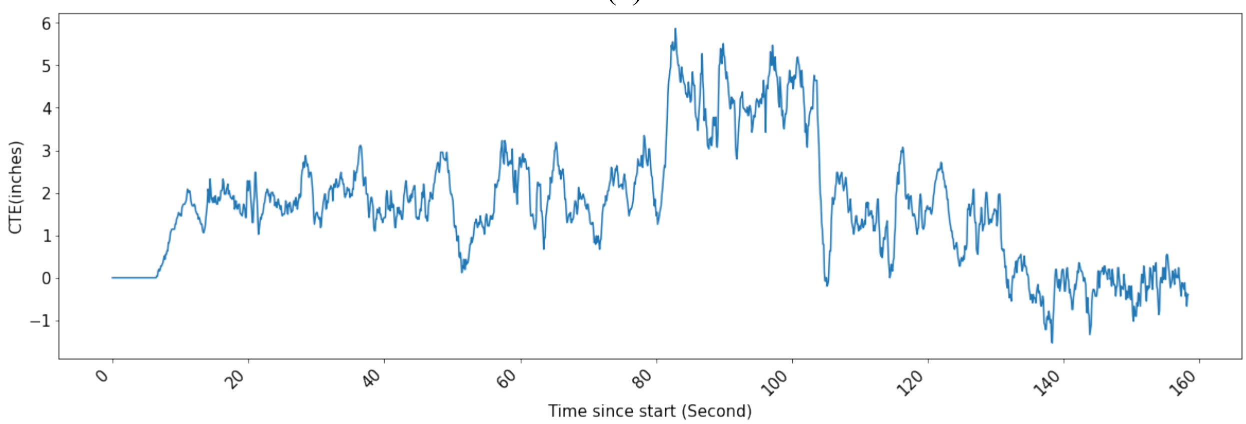
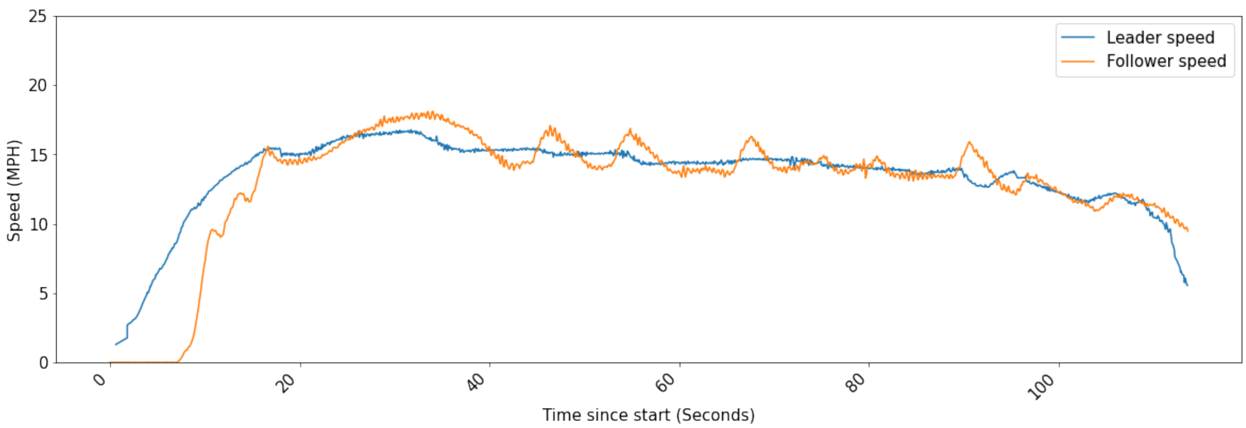


(c)

Figure B.67 Test case 12, Run 6: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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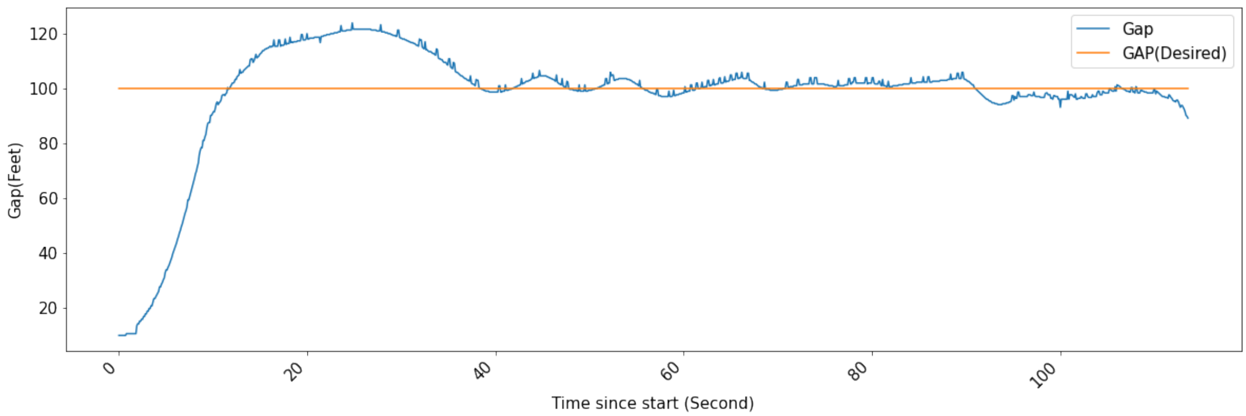

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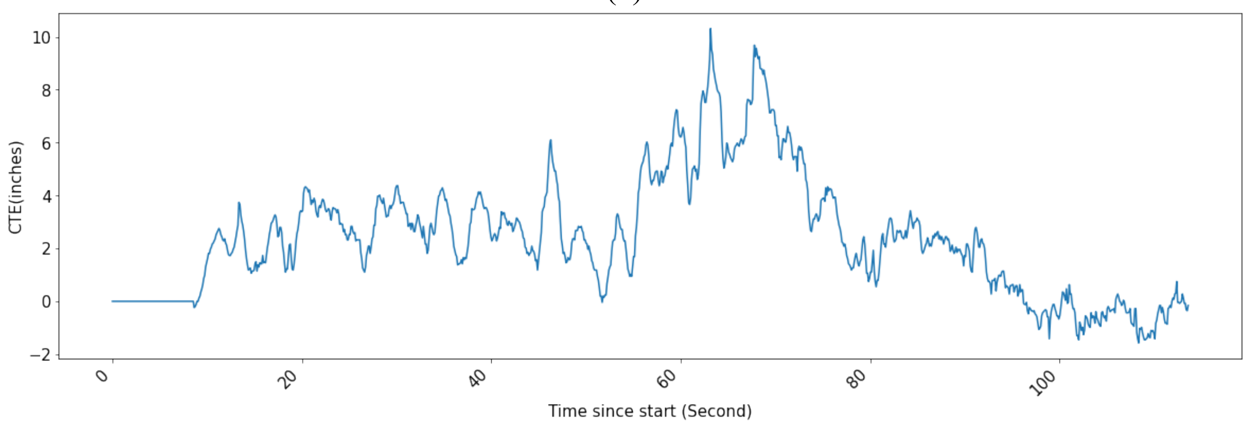
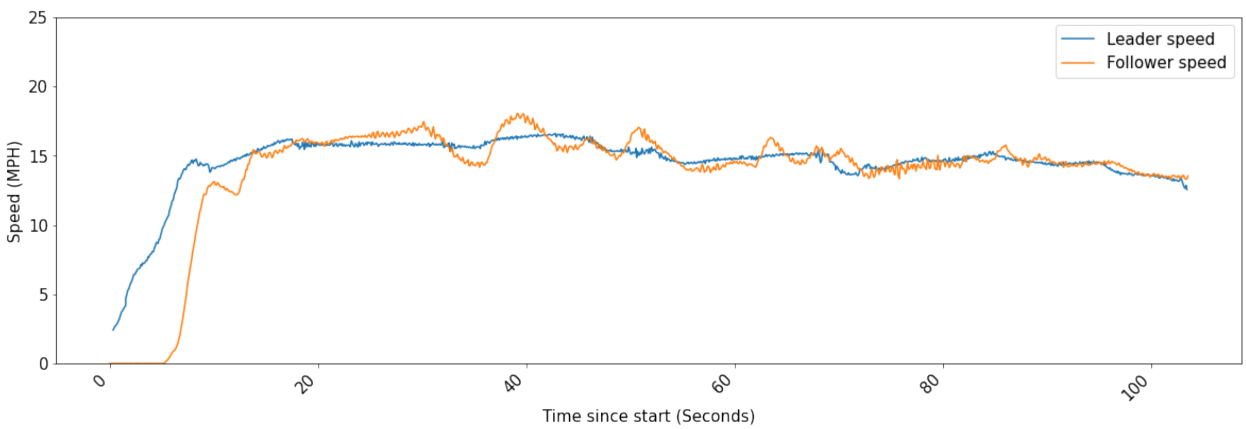


(c)

Figure B.68 Test case 12, Run 7: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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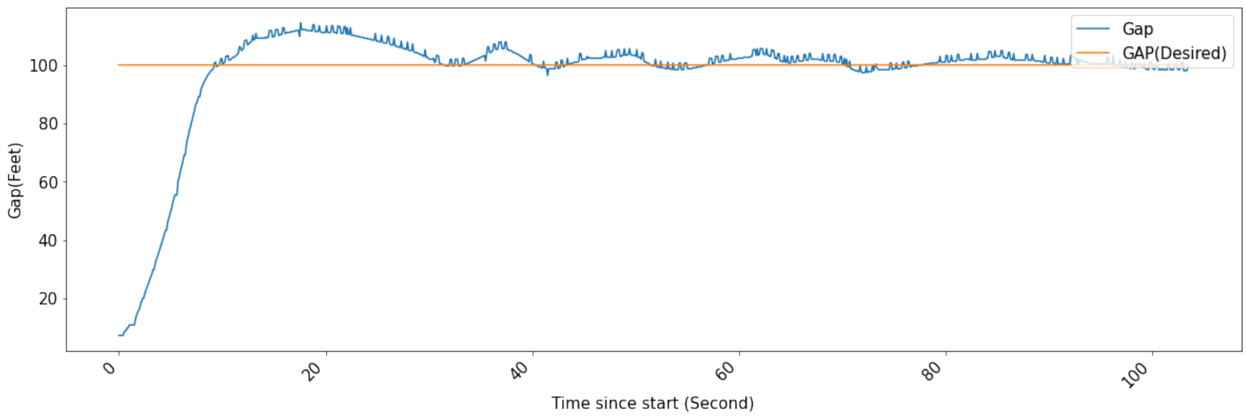

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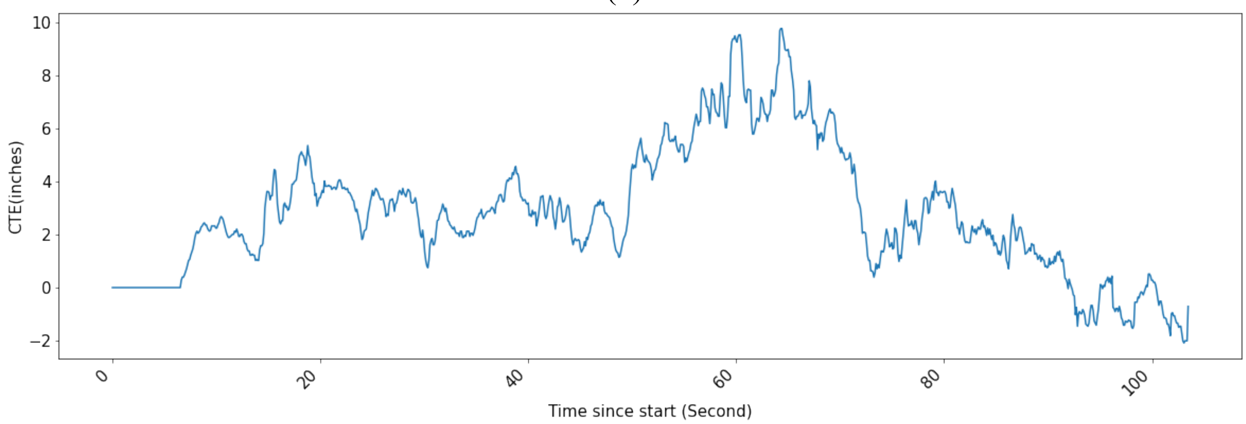
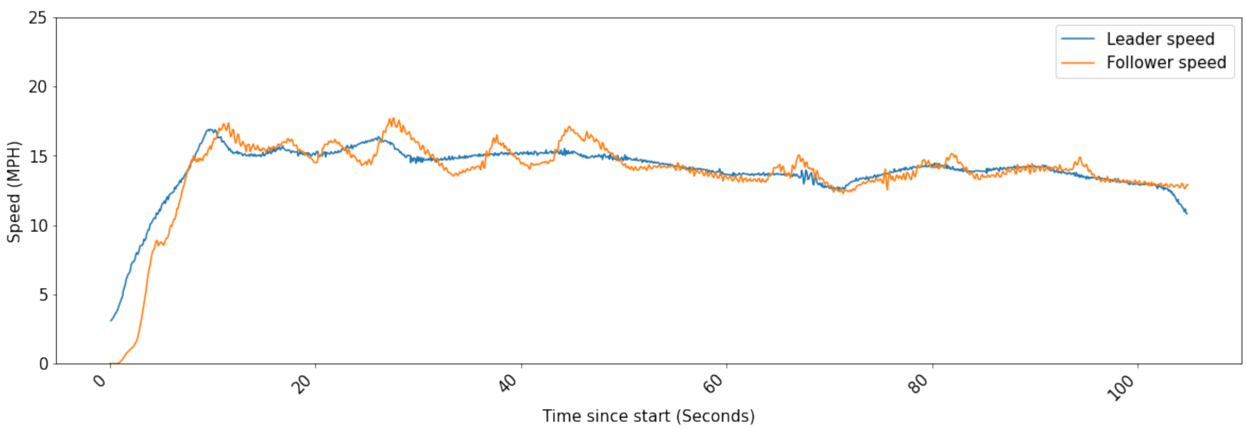


(c)

Figure B.69 Test case 12, Run 8: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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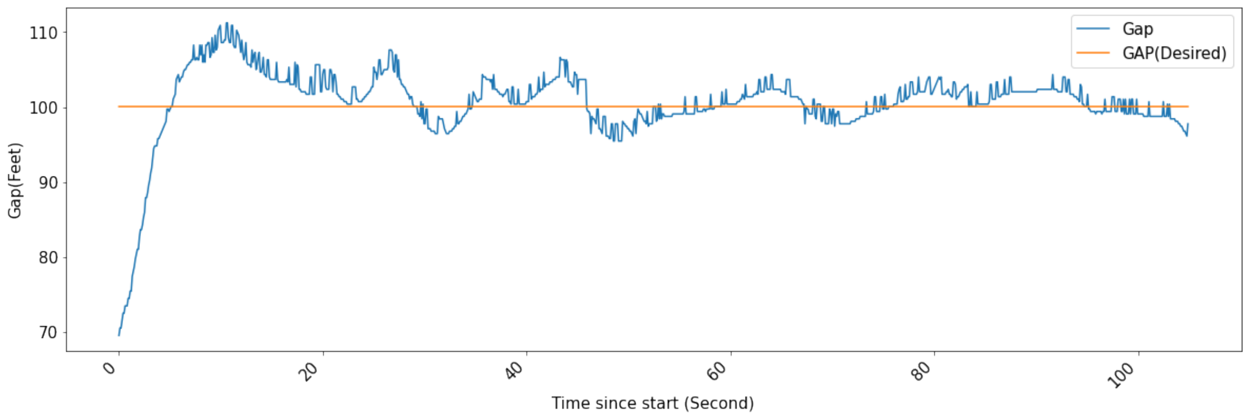

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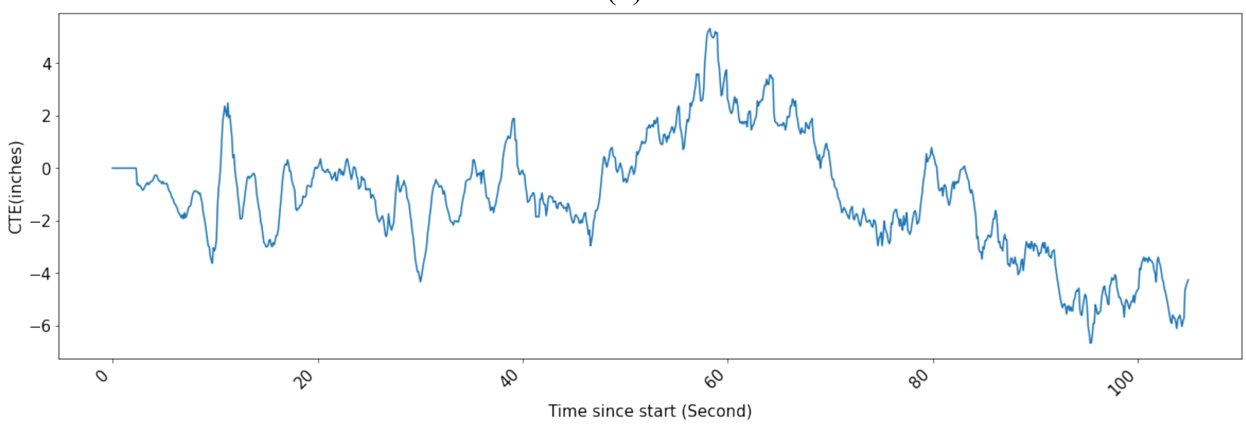


(c)

Figure B.70 Test case 12, Run 9: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.

Test Case 13: Roundabouts

Table B.31 Test Procedure-Test Case 13

Operation procedure	• Placed the traffic cones to form the roundabout with a 65 feet radius and 12 feet width. • Activated the leader truck and ATMA at 5 mph to pass the roundabout. • Conducted 3 runs for each speed.
Data collection	• Collected ATMA lateral accuracy.
Expected results	The ATMA maintains a lateral accuracy of ±6 inches when passing the roundabouts.
Total number of runs	4 runs
Supporting equipment	Walkie-talkie, Traffic cones
Supporting staff from INDOT	Leader vehicle driver, ATMA driver, ATMA operator in leader vehicle

Four runs of the roundabout test were finished successfully as shown in Table B.32. However, due to space limitations, it was difficult to line up and start the automated mode of the ATMA system.

Four runs of roundabout tests were finished in one continuous run. The max gap difference, min gap difference, average gap difference, and std. gap difference during the roundabout test is 312.34 feet, -12.80 feet, 56.72 feet, and 92.72 feet. The max CTE, min CTE, average CTE, and std. CTE are 11.65 inches, -11.38 inches, -1.12 inches, and 3.016 inches, respectively. The max CTE and min CTE are not in the range of ±6 inches. Figure B.71 and Figure B.72 show the trajectory of leader and follower trucks in the roundabout test. Figure B.73 shows the leader truck speed vs. follower truck speed, the gap vs. the desired gap, and CTE during the roundabout test. The results show the ATMA needs to reduce speed to 0 mph to follow the trajectory of the leader truck. Therefore, the gap difference kept increasing to a maximum of 312.34 feet during the roundabout test.

Table B.32 Data Collection Form-Test Case 13

Runs	Test Speed	Finished or not
1	5 mph	Yes
2	5 mph	Yes
3	5 mph	Yes
4	5 mph	Yes

Figure B.71 The trajectory of the leader (yellow) and follower (blue) in the roundabout test.

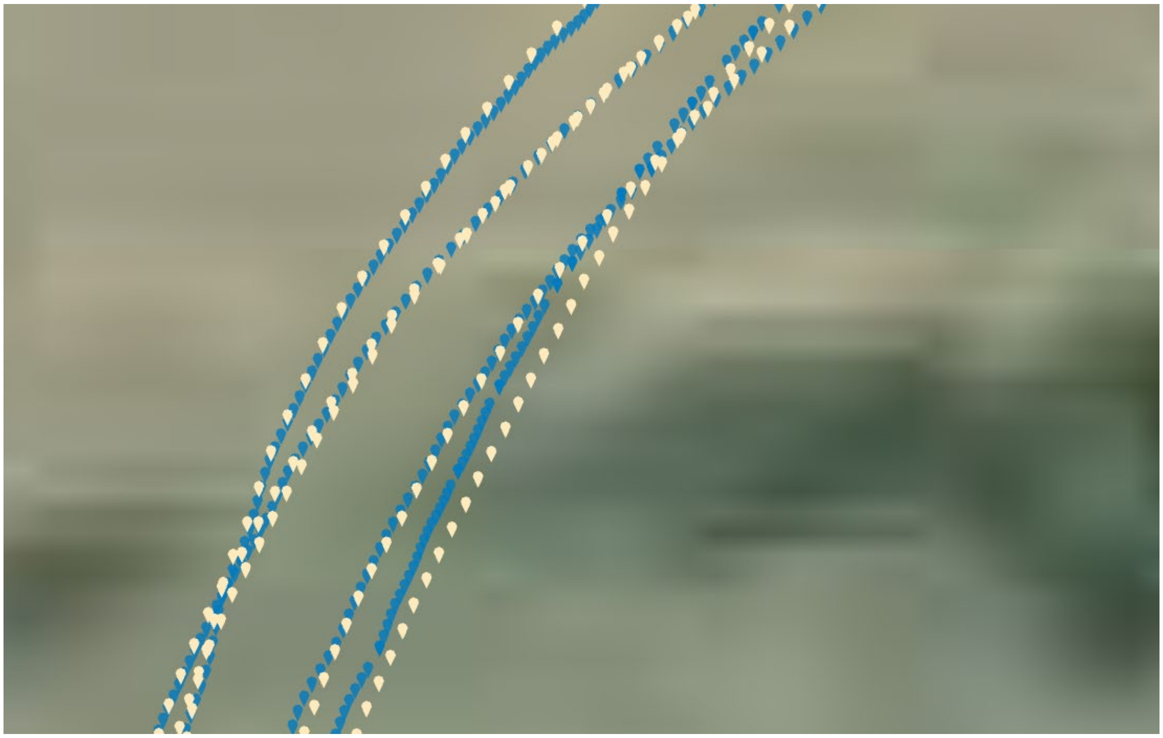
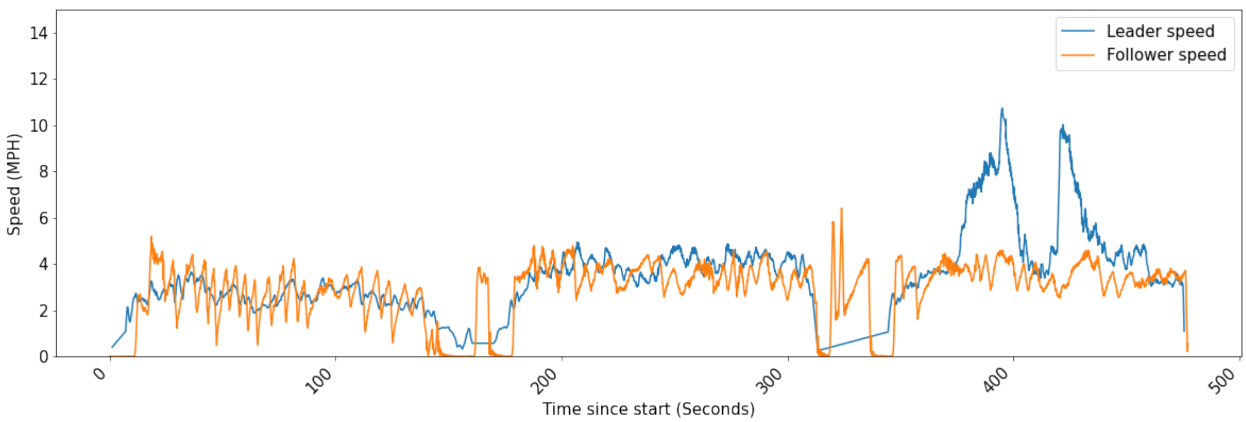


Figure B.72 The trajectory of the leader (yellow) and follower (blue) in the roundabout test zoomed in.



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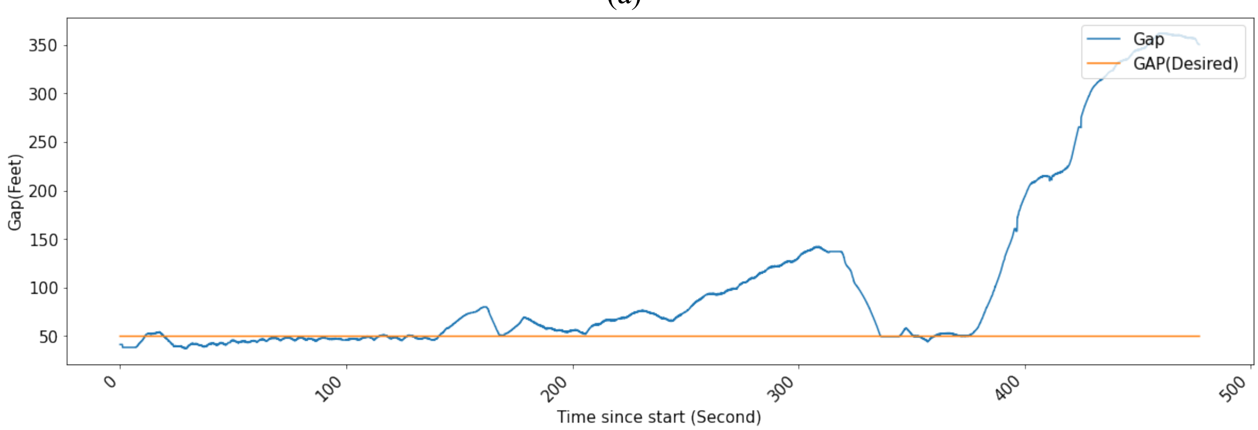

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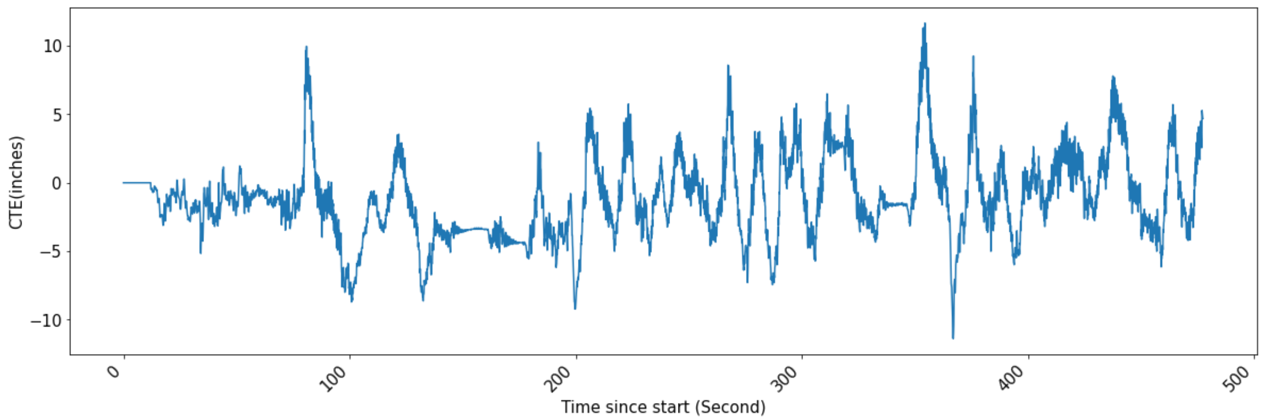


(c)

Figure B.73 Test case 13, (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.

B.5 Focus Area 5: Obstacle

Test Case 14: Obstacle Detection–Front

Table B.33 Test Procedure-Test Case 14

Operation procedure	• Activated the leader truck and ATMA with a 100 feet gap and drive at 5 mph. • Put the obstacle into the ATMA path after the leader truck passes. • Conducted 3 runs for each speed. • Repeated at 10 mph and 15 mph.
Data collection	• Measured the distance between the stopped ATMA location and the traffic barrel. • Collected the ATMA log files.
Expected results	The ATMA should detect the traffic barrel and execute an A-stop.
Total number of runs	9 runs
Supporting equipment	Walkie-talkie, Traffic cones, Traffic barrel, Measuring wheel
Supporting staff from INDOT	Leader vehicle driver, ATMA driver, ATMA operator in leader vehicle, one crew to pull the barrel

The ATMA was able to detect the traffic barrel and executed an A-stop. The detailed results are recorded in Table B.34.

Table B.34 Data Collection Form-Test Case 14

Runs	Test Speed	ATMA Stop or Not (Yes/No)	Distance between the Stopped ATMA Location and Traffic Barrel (feet)
1	5 mph	Yes	89
2	5 mph	Yes	87
3	5 mph	Yes	90
4	10 mph	Yes	85
5	10 mph	Yes	79
6	10 mph	Yes	79
7	15 mph	Yes	76
8	15 mph	Yes	74
9	15 mph	Yes	77

Test Case 15: Obstacle Detection–Side

Table B.35 Test Procedure-Test Case 15

Operation procedure	• Activated the leader truck and ATMA with 100 feet gap and drive at 5 mph. • Placed the obstacle (traffic barrel) on the left side of the ATMA. • Repeated for the right side. • Conducted 3 runs for each speed. • Repeated at 10 mph and 15 mph.
Data collection	• Measure the distance between the stopped ATMA location and the traffic barrel. • Collect the ATMA log data.
Expected results	The ATMA should operate normally if the obstacles are not in its path.
Total number of runs	18 runs
Supporting equipment	Walkie-talkie, Traffic cones, Traffic barrel, Measuring wheel
Supporting staff from INDOT	Leader vehicle driver, ATMA driver, ATMA operator in leader vehicle, one crew to pull the barrel

18 runs were conducted successfully. The ATMA can detect the side object and display the warning message on the UI. In addition, the ATMA did not stop for the side object as shown in Table B.36.

Table B.36 Data Collection Form-Test Case 15 – Traffic Barrel

Runs	Test Speed	Side	ATMA Sensor detected the obstacle	ATMA stopped or not
1	5 mph	Left	Left side LIDAR	No
2	5 mph	Left	Left side LIDAR	No
3	5 mph	Left	Left side LIDAR	No
4	5 mph	Right	Right side LIDAR	No
5	5 mph	Right	Right side LIDAR	No
6	5 mph	Right	Right side LIDAR	No
7	10 mph	Left	Left side LIDAR	No
8	10 mph	Left	Left side LIDAR	No
9	10 mph	Left	Left side LIDAR	No
10	10 mph	Right	Right side LIDAR	No
11	10 mph	Right	Right side LIDAR	No
12	10 mph	Right	Right side LIDAR	No
13	15 mph	Left	Left side LIDAR	No
14	15 mph	Left	Left side LIDAR	No
15	15 mph	Left	Left side LIDAR	No
16	15 mph	Right	Right side LIDAR	No
17	15 mph	Right	Right side LIDAR	No
18	15 mph	Right	Right side LIDAR	No

Test Case 16: Vehicle Intrusion

Table B.37 Test Procedure-Test Case 16

Operation procedure	• Activated the leader truck and ATMA with a 300 feet gap and drive at 5 mph. • Drove the vehicle and cut in the path of ATMA. • Conducted 3 runs for each speed. • Repeated at 10 mph and 15 mph.
Data collection	• Collected ATMA log data. • Measured the stopping distance of ATMA. • Measured the stopping time of ATMA.
Expected results	The ATMA should detect the vehicle and execute an A-stop.
Total number of runs	9 runs
Supporting equipment	Walkie-talkie, Traffic cones, Vehicle, Measuring wheel
Supporting staff from INDOT	Leader vehicle driver, ATMA driver, ATMA operator in leader vehicle, one crew to drive another vehicle

The ATMA detected the vehicle as a front obstacle and initiated A-stop. The distances between the stopped ATMA and the stopped vehicle for each run are shown in Table B.38.

Table B.38 Data Collection Form-Test Case 16

Runs	Test Speed	Distance between the Stopped ATMA and Stopped Vehicle
1	5 mph	96
2	5 mph	67
3	5 mph	83
4	10 mph	29
5	10 mph	83
6	10 mph	77
7	15 mph	72
8	15 mph	71
9	15 mph	83

Test Case 17: Bump Obstacle Test

Table B.39 Test Procedure-Test Case 17

Operation procedure	• Activated the leader truck and ATMA with a 300 feet gap and drive at 5 mph. • Put a bump in the ATMA path. • Conducted 3 runs for each speed. • Repeated at 10 mph and 15 mph.
Data collection	• Collected ATMA following accuracy. • Checked if ATMA stops.
Expected results	The ATMA should maintain lane accuracy over minor obstructions in the roadway.
Total number of runs	9 runs
Supporting equipment	Walkie-talkie, Traffic cones, Bump obstacle (Speed bump), Measuring wheel
Supporting staff from INDOT	Leader vehicle driver, ATMA driver, ATMA operator in leader vehicle

The ATMA was able to pass the speed bump without any stops as shown in Table B.40. The speed bump was not detected as an obstacle that caused A-stop.

Table B.40 Data Collection Form-Test Case 17

Runs	Test Speed	ATMA Stop or not (Yes/No)
1	5 mph	No
2	5 mph	No
3	5 mph	No
4	10 mph	No
5	10 mph	No
6	10 mph	No
7	15 mph	No
8	15 mph	No
9	15 mph	No

B.6 Focus Area 6: Operational Test

Test Case 18: Speed to Catching Up with the Gap

Table B.41 Test Procedure-Test Case 18

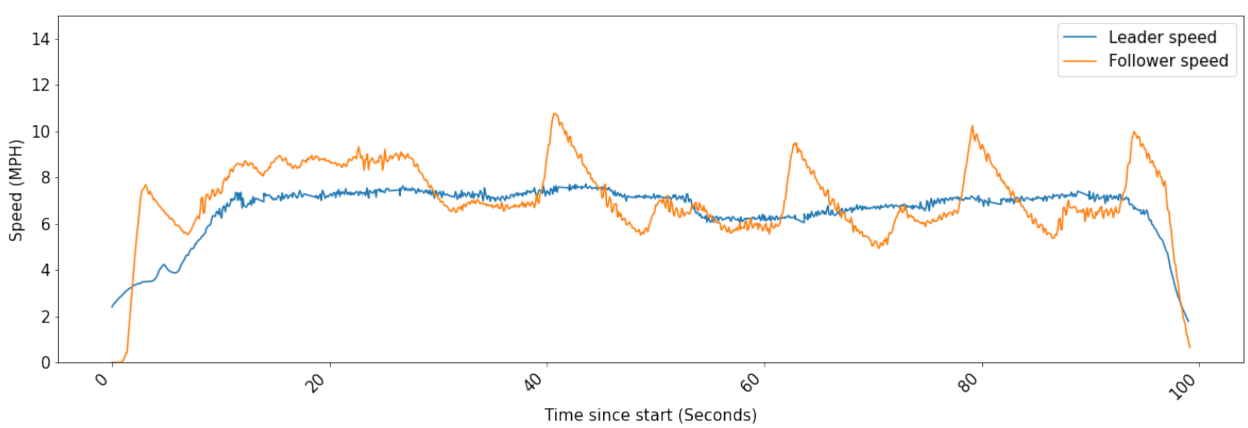
Operation procedure	• Activated the leader truck and ATMA with a 150 feet gap and drive at 5 mph. • Commanded the gap as 100 feet. • Tested when the ATMA can catch up the gap to 100 feet.
Data collection	• Collected ATMA log data. • Measured the time to catch the gap. • Collected maximum speed in catching the gap.
Expected results	The ATMA should catch the gap and the catch-up speed should not exceed 20 mph.
Total number of runs	9 runs

The ATMA cannot be activated until the actual gap was reduced to 150 feet. The error message in the UI was "outside rollout allowance range". Due the space limitations, only 5 mph operations were performed. The only successful case was activated the leader truck and ATMA with 150 feet gap and the command the gap as 100 feet. The reason is ATMA's maximum rollout allowance distance is 246 feet after confirmation with Kratos by email.

The time taken to catch up the gap was 40.98 seconds and the maximum speed during gap catch-up is 10.77 mph as shown in Table B.42. Figure B.74 displays leader truck speed vs. follower truck speed, gap vs. the desired gap, and CTE during the test.

Table B.42 Data Collection Form-Test Case 18

Runs	Test Speed	Gap Changes	Time to Catch up with the Leader Truck (Seconds)	Maximum Speed (mph)
1	5 mph	150 feet → 100 feet	40.98	10.77



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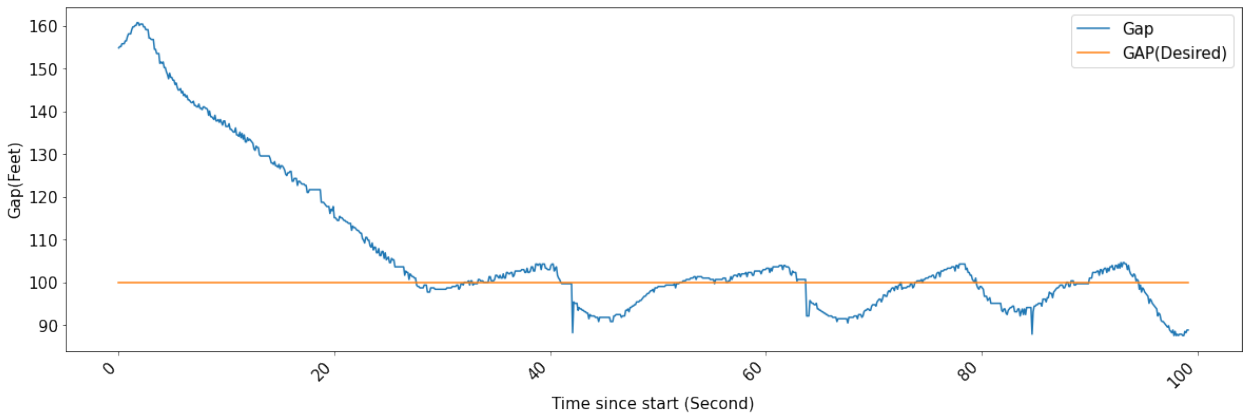

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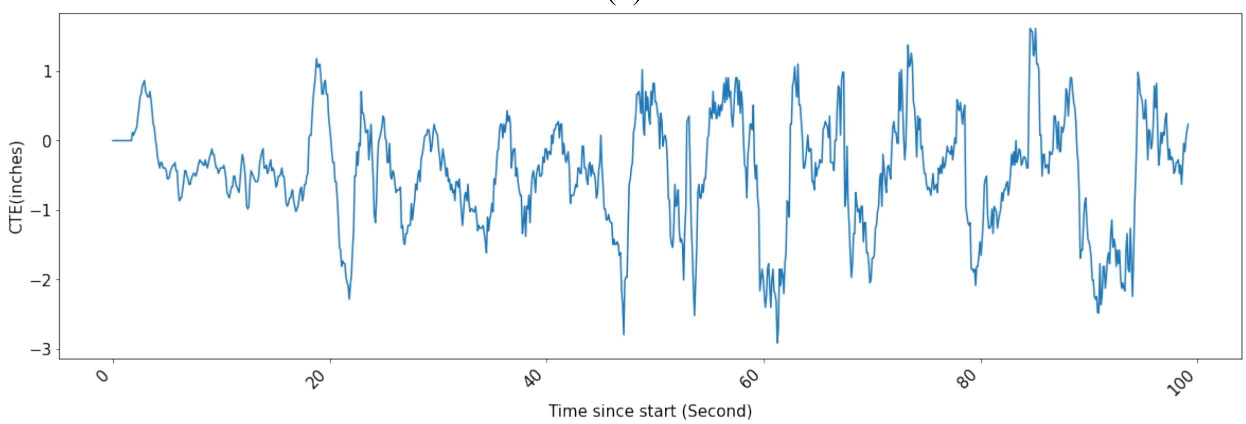


(c)

Figure B.74 Test case 18 (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.

Test Case 19: Braking–Leader Vehicle

Table B.43 Test Procedure-Test Case 19

Operation procedure	• Placed three lines of traffic cones in the center of the road and on both edges of the road. Each line had three traffic cones with 20 feet spacing. • Activated the leader truck and ATMA. • Drove the leader truck in a straight line at 5 mph. • Initiated "stop" command when the front of ATMA passed traffic cones in the middle column. • Braked the leader truck hard. • Conducted 3 runs for each speed. • Repeated at 10 mph and 15 mph.
Data collection	• Collected ATMA log data. • Measured the stopping distance of ATMA with a measuring wheel. • Measured the stopping time of ATMA with a stopwatch.
Expected results	The ATMA should stop when the leader vehicle brakes hard.
Total number of runs	9 runs
Supporting equipment	Walkie-talkie
Supporting staff from INDOT	Leader vehicle driver, ATMA driver, ATMA operator in leader vehicle

The ATMA was able to stop when the leader truck braked hard. The stopping distance and stopping time for each run are in Table B.44. The stopping distance and stopping time were longer than the A-stop. The reason might be the ATMA needs to detect if the leader is stopped from the leader truck's trajectory.

Table B.44 Data Collection Form-Test Case 19

Runs	Test Speed	Stopping Distance (feet)	Stopping Time (seconds)
1	5 mph	59.2	12.84
2	5 mph	27.9	11.03
3	5 mph	55.6	12.41
4	10 mph	77.1	12.40
5	10 mph	46.0	5.29
6	10 mph	40.3	5.03
7	15 mph	59.0	5.00
8	15 mph	132.0	18.19
9	15 mph	61.0	5.59

Test Case 20: Leader–Reverse

Table B.45 Test Procedure-Test Case 20

Operation procedure	• Activated the leader truck and ATMA with a 300 feet gap and drove at 5 mph. • Conducted 3 runs for each speed. • Reversed the leader truck. • Repeated at 10 mph and 15 mph.
Data collection	• Collected ATMA log data.
Expected results	The ATMA should stop when the leader vehicle reverses.
Total number of runs	9 runs
Note	The e-crumb error was generated when the leader started to reverse.

The ATMA can initiate A-stop if the leader truck was reversing for all runs.

Table B.46 Data Collection Form-Test Case 20

Runs	Test Speed	ATMA Stop or Not (Yes/No)
1	5 mph	Yes
2	5 mph	Yes
3	5 mph	Yes
4	10 mph	Yes
5	10 mph	Yes
6	10 mph	Yes
7	15 mph	Yes
8	15 mph	Yes
9	15 mph	Yes

Test Case 21: Acceleration/Deceleration

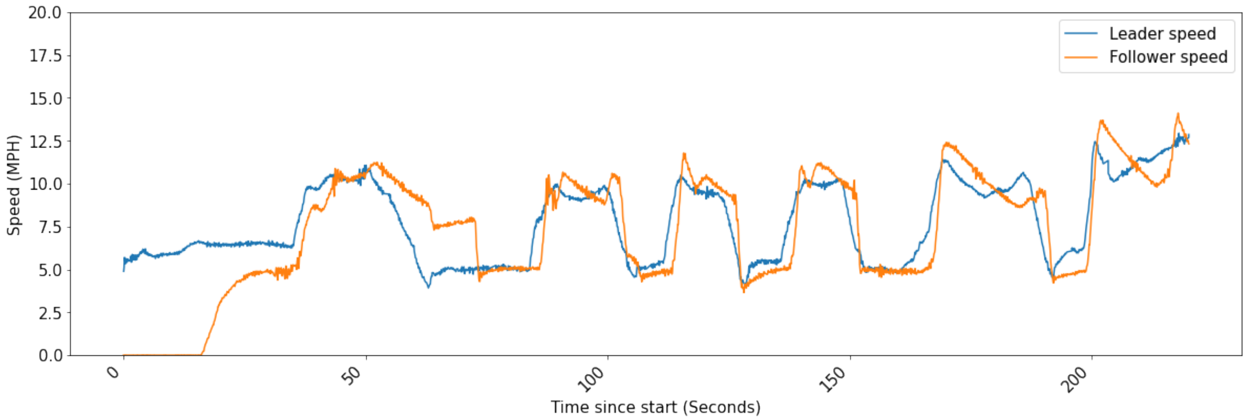
Table B.47 Test Procedure-Test Case 21

Operation procedure	• Activated the leader truck and ATMA with a 300 feet gap and drove at 5 mph. • Increased the speed to 10 mph. • Decreased the speed to 5 mph. • Conducted 3 runs for each speed change. • Repeated for 5→ 15→ 5 mph and 5→ 20→ 5 mph.
Data collection	• Measured the time for ATMA to be operated at the new speed.
Expected results	The ATMA should be able to adjust for the new speed.
Total number of runs	6 runs (Each run has two subtasks.)

The 5 mph → 20 mph case was not finished due to the space limitation. Figure B.75 and Figure B.76 show the leader truck speed vs. follower truck speed, gap vs. the desired gap, and CTE for each run.

Table B.48 Data Collection Form-Test Case 21

Runs	Test Speed	Finished or not
1a	5 mph → 10 mph	Yes
1b	10 mph → 5 mph	Yes
2a	5 mph → 10 mph	Yes
2b	10 mph → 5 mph	Yes
3a	5 mph → 10 mph	Yes
3b	10 mph → 5 mph	Yes
4a	5 mph → 15 mph	Yes
4b	15 mph → 5 mph	Yes
5a	5 mph → 15 mph	Yes
5b	15 mph → 5 mph	Yes
6a	5 mph → 15 mph	Yes
6b	15 mph → 5 mph	Yes



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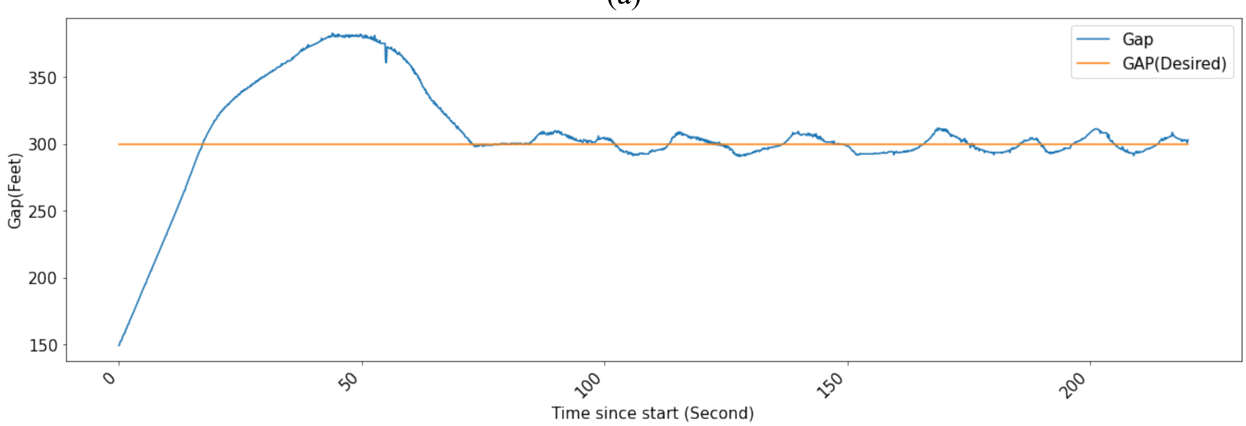

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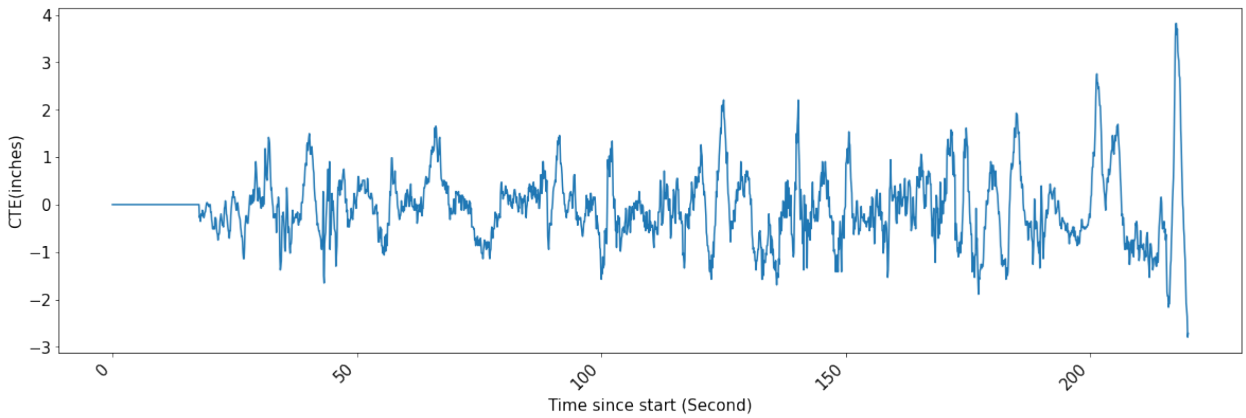
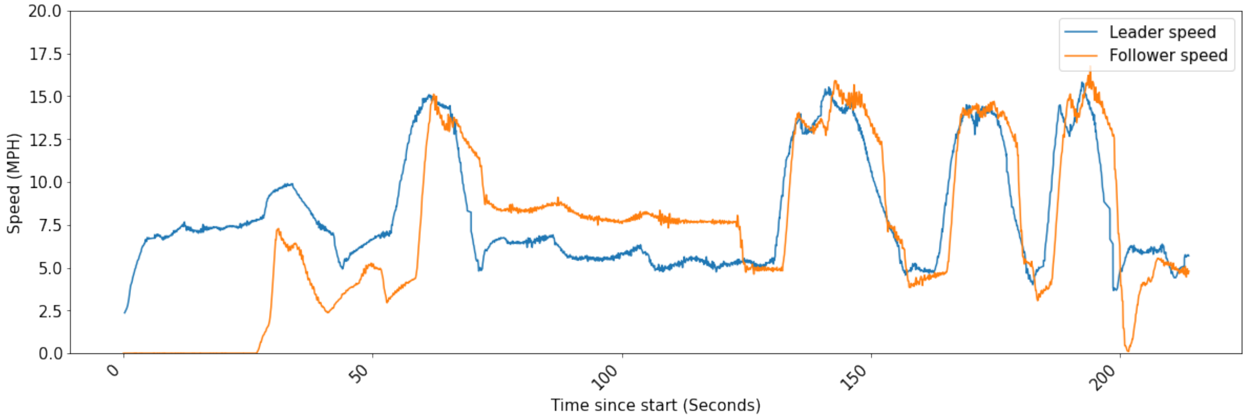


(c)

Figure B.75 Test case 21, Run 1: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.



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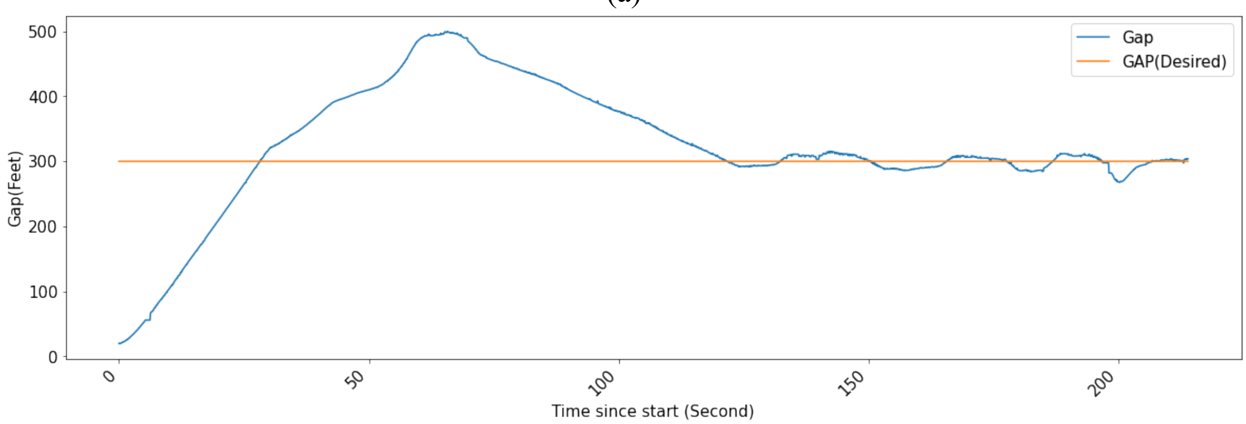

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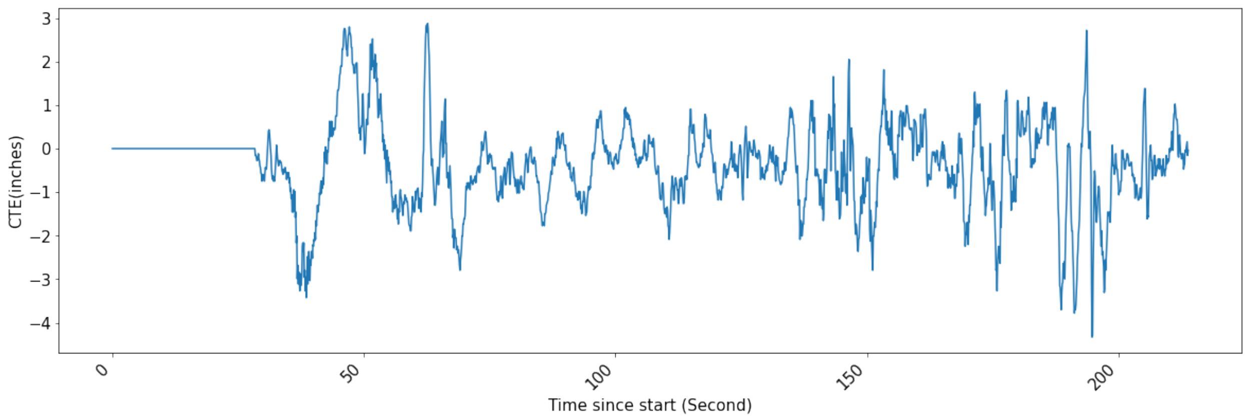

(c)

Figure B.76 Test case 21, Run 2: (a) leader truck speed vs. follower truck speed, (b) gap vs. desired gap, (c) CTE.

B.7 Focus Area 7: Loss of Communication

Test Case 22: Downgraded GPS Signal–60 Seconds

Table B.49 Test Procedure-Test Case 22

Operation procedure	• Activated the leader and ATMA with 100 feet gap and drive in a straight line at 5 mph. • Downgraded the ATMA GPS signal for 60 seconds by setting the follower truck not receiving the GPS signal. • Conducted 3 runs for each speed.
Data collection	• Collected the ATMA log. • Checked if the ATMA can be operated normally with a downgraded GPS signal.
Expected results	• The ATMA should be operated for a while (around 60 seconds) when the GPS signal is downgraded. • The ATMA should be operated normally after the GPS signal resumes.
Total number of runs	3 runs

The result of the test is recorded in Table B.50.

Table B.50 Data Collection Form-Test Case 22

Runs	Leader / ATMA GPS Signal Downgraded	Speed	ATMA Stop or Not (Yes/No)	ATMA operated for 60 seconds (Yes/No)
1	Leader	5 mph	No	Yes
2	Leader	5 mph	No	Yes
3	Leader	5 mph	No	Yes

Test Case 23: Downgraded GPS Signal–Forever

Table B.51 Test Procedure-Test Case 23

Operation procedure	• Activated the leader and ATMA and drive in a straight line at 5 mph with 100 feet following distance. • Downgraded the ATMA GPS signal by covering the GPS antennas of the leader truck with shields. • Conducted 3 runs for each speed.
Data collection	• Collected the ATMA log file. • Recorded GPS signal quality after GPS antennas are covered. • Measured the time that ATMA can be operated normally after the GPS signal is downgraded. • Measured the distance to stop. • Measured the time to stop.
Expected results	• The ATMA should be operated for a while after the GPS signal is downgraded. • The ATMA should be stopped at the end.
Total number of runs	3 runs

Only 5 mph was performed due to safety concerns. The time to stop was calculated from the log files. Table B.52 shows the time to stop for each downgraded GPS signal is 12.34, 54.83, and 64.94 seconds, respectively.

Table B.52 Data Collection Form-Test Case 23

Runs	Leader / ATMA GPS Signal Downgraded	Speed	ATMA Stop or Not (Yes/No)	Time to Stop (Seconds)
1	Leader	5 mph	Yes	12.34
2	Leader	5 mph	Yes	54.83
3	Leader	5 mph	Yes	64.94

Test Case 24: Loss of Communication (Single V2V Radio)

Table B.53. Test Procedure-Test Case 24

Operation procedure	• Activated the leader and ATMA and drive in a straight line at 5 mph with 100 feet following distance. • Disconnected the primary Ethernet cable connecting the radios and the systems control unit (SCU) or the network switch. • Reconnected the primary Ethernet cable. • Disconnected the secondary Ethernet cable connecting the radios and SCU or the network switch. • Reconnected the secondary Ethernet cable. • Conducted 3 runs for 5 mph.
Data collection	• Collected the ATMA log file. • Recorded error massage.
Expected results	• The ATMA should be operated normally with the loss of one V2V radio. • The ATMA system notifies the error message to the operator.
Total number of runs	3 runs (Each run has two subtasks.)
Supporting equipment	Walkie-talkie
Supporting staff from INDOT	Leader vehicle driver, ATMA driver, ATMA operator in leader vehicle

The ATMA can be operated automatically with the loss of one V2V radio as shown in Table B.54.

Table B.54 Data Collection Form-Test Case 25

Runs	Speed	Ethernet Cable Disconnected	ATMA Stop or Not (Yes/No)
1a	5 mph	Primary	No
1b	5 mph	Secondary	No
2a	5 mph	Primary	No
2b	5 mph	Secondary	No
3a	5 mph	Primary	No
3b	5 mph	Secondary	No

Test Case 25: Loss of Communication (Both V2V Radio)

Table B.55 Test Procedure-Test Case 25

Operation procedure	• Activated the leader and ATMA and drive in a straight line at 5 mph and set the gap to 100 feet. • Disconnected both Ethernet cables connecting the radios and the SCU or the network switch. • Conducted 3 runs for 5 mph.
Data collection	• If ATMA was stopped or not.
Expected results	• The ATMA should stop with the loss of both V2V radios.
Total number of runs	3 runs
Supporting equipment	Walkie-talkie, Measuring wheel
Supporting staff from INDOT	Leader vehicle driver, ATMA driver, ATMA operator in leader vehicle

The ATMA initiated a nonrecoverable A-stop with the loss of both V2V radios as shown in Table B.56.

Table B.56 Data Collection Form-Test Case 25

Runs	Speed	ATMA Stop or Not (Yes/No)
1	5 mph	Yes
2	5 mph	Yes
3	5 mph	Yes

APPENDIX C. WORKERS' PERCEPTION OF THE ATMA SYSTEM

ATMA Survey

Part 1: Demographic Information

1. What state DOT do you work for?

   ____
2. How long have you worked for the DOT?
   - Less than one year
   - One to three years
   - Three years to 10 years
   - More than 10 years
3. How long have you worked for the following mobile work zone operations?
   - Crack sealing _______________
   - Pothole patching _______________
   - Trash pickup _______________
   - RMP inspection _______________
   - Underdrain inspection _______________
4. What is your experience with ATMA?
   - I have operated the ATMA for open road tests.
   - I have operated the ATMA for close road tests.
   - I have seen the operation/demonstration of the ATMA system.
   - I have heard from ATMA who operated it before.
   - I have never heard about ATMA.
   - Other_____

Part 2: Evaluation of the ATMA User Interface

5. On a scale of 1 (Fully disagree) to 5 (Fully agree), please indicate how much you agree with the following statements about the user interface:
    1 (Fully disagree)
    2 (Disagree)
    3 (Neither agree nor disagree)
    4 (Agree)
    5 (Fully Agree)

Statements	Your evaluation
The user interface is easy to operate.	
The user interface is stable in daily operations.	
The displayed information is clear to me.	
The type of information is sufficient for operation.	

6. On a scale of 1 (Not effective at all) to 5 (Extremely effective), please rate the overall effectiveness of each type of information in the user interface from location and size perspectives:
    1 (Not effective at all)
    2 (Somewhat effective)
    3 (Moderately effective)
    4 (Effective)
    5 (Extremely effective)

	Location	Size
Warning signal		
GPS status		
V2V link		
Vehicle gap		
Lateral offset		
DR status		
Rear-facing camera		
Front-facing camera		

7. Is there any other information that needs to be displayed on the display? If yes, please specify.

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8. On a scale of 1 (Not effective at all) to 5 (Extremely effective), please rate the overall effectiveness of the user interface for each operation:
    1 (Not effective at all)
    2 (Somewhat effective)
    3 (Moderately effective)
    4 (Effective)
    5 (Extremely effective)

	Evaluation
Setting up the gap	
Setting up the lateral offset	
Clear up the warning information	

Part 3: Evaluation of ATMA System Automation

9. On a scale of 1 (Not confident at all) to 5 (Extremely confident), please rate how confident you are in the ability of ATMA to operate automatically for various tasks under different weather conditions.
    1 (Not confident at all)
    2 (Somewhat confident)
    3 (Moderately confident)
    4 (Confident)
    5 (Extremely confident)

	Clear	Rain	Dark	Snow
Crack sealing				
Pothole patching				
Trash pickup				
Underdrain inspection				
RMP inspection				

10. On a scale of 1 (Not confident at all) to 5 (Extremely confident), please rate how confident you are in the ability of ATMA to operate automatically for the following road conditions.
    1 (Not confident at all)
    2 (Somewhat confident)
    3 (Moderately confident)
    4 (Confident)
    5 (Extremely confident)

	Evaluation
Interstate (e.g. I465)	
Arterial	
Trunk Highway (e.g. US31)	
State Road (e.g. SR19)	

11. On a scale of 1 (Not confident at all) to 5 (Extremely confident), please rate how confident you are in the ability of ATMA to operate automatically for the following cases.
    1 (Not confident at all)
    2 (Somewhat confident)
    3 (Moderately confident)
    4 (Confident)
    5 (Extremely confident)

	Evaluation
Passing overhead bridge	
Passing traffic signal	
Passing roundabout	
Passing intersection	
Changing lane	

Part 4: Evaluation of ATMA System Impact on Safety and Productivity

12. On a scale of 1 (Fully disagree) to 5 (Fully agree), please indicate how much you agree with the following statements:
    1 (Fully disagree)
    2 (Disagree)
    3 (Neither agree nor disagree)
    4 (Agree)
    5 (Fully Agree)

	Evaluation
My productivity is improved for *crack sealing* operations when ATMA is used.	
My productivity is improved for *pothole patching* operations when ATMA is used.	
My productivity is improved for *trash pickup* operation when ATMA is used than TMA.	
My productivity is improved for *underdrain inspection* operations when ATMA is used.	
My productivity is improved for *RMP* inspection operations when ATMA is used.	

13. On a scale of 1 (Fully disagree) to 5 (Fully agree), please indicate how much you agree with the following statements:
    1 (Fully disagree)
    2 (Disagree)
    3 (Neither agree nor disagree)
    4 (Agree)
    5 (Fully Agree)

	Evaluation
Using ATMA system for *crack sealing* operations is safer than using TMA.	
Using ATMA system for *pothole patching* operations is safer than using TMA.	
Using ATMA system for *trash pickup* operations is safer than using TMA.	
Using ATMA system for *underdrain inspection* operations is safer than using TMA.	
Using ATMA system for *RMP inspection* operations is safer than using TMA.	

Part 5: Other Comments

14. Please share any other comments/suggestions related to the ATMA system.

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About the Joint Transportation Research Program (JTRP)

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

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

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

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

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