VALIDATION DATA REPORT

FOR THE

COLORADO DEPARTMENT OF TRANSPORTATION AUTONOMOUS TRUCK MOUNTED ATTENUATOR VALIDATION EVENT

CONTRACT NO.: AAAQ33546A

CDRL: N/A

CLASSIFICATION: Unclassified

Prepared For:
INTERNAL USE ONLY

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DOCUMENT REVISION RECORD			
REV	**DESCRIPTION OF CHANGE**	**DATE**	**ORIGINATOR**
-	Initial Release	7/17/2017	W. Kyaw

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ACRONYM LIST

Acronym	Description
ALT	Altitude
ATMA	Autonomous Truck Mounted Attenuator
CDOT	Colorado Department of Transportation
CDRL	Contract Data Requirements List
CSV	Comma Separated Value
CTE	Cross Track Error
eCrumbs	Electronic Crumbs
ESR	Electronically Scanning Radar
E-Stop	Emergency Stop
GPS	Global Positioning System
ID	Identification
KML	Keyhole Markup Language
LAT	Latitude
LON	Longitude
M-PAK	Multi-Platform Applique Kit
MPH	Mile per Hour
N/A	Not Applicable
TMA	Truck Mounted Attenuator

1.0 INTRODUCTION

The Colorado Department of Transportation (CDOT) organized a test event to characterize the Autonomous Truck Mounted Attenuator (ATMA) system developed by Micro Systems Inc.

The ATMA is an innovative system which uses the leader-follower concept. The leader truck, operated by a human driver, is equipped with a Global Positioning System (GPS) instrument, which drops electronic crumbs (eCrumbs) containing the position information for the follower. The follower vehicle, usually a Truck Mounted Attenuator (TMA) truck, is designed to operate autonomously following those eCrumbs at a configured gap distance. The system is designed to eliminate injury to a TMA operator in the event of a traffic accident.

The test scenarios were planned and outlined by CDOT for each day. The period of testing using structured test cases was from June 27, 2017 to June 29, 2017. The demonstration of the system was conducted on the following day, June 30, 2017 for the attending personnel.

2.0 APPLICABLE DOCUMENTS

2.1 Non-Government Documents

N/A

3.0 TEST DATA

During each test scenario, the log file generated by the ATMA system on the follower vehicle was collected. The log file can be analyzed to gain insights on the performance and behavior of the system, especially about the follower vehicle.

3.1 Limitations

Certain test scenarios required the follower vehicle to operate in IDLE mode. In those cases, speed, velocity, steering, throttle, and brake data are not available. Similarly, the follower stops collecting data after an E-Stop event. The reader will have to use the manually collected test results for those cases.

3.2 Vehicle Operating Mode

Most log files recorded the transition of the vehicle operating modes from beginning of the test scenario to the end. A test event may usually, but not always, begin with the follower vehicle in a power cycled state. The follower will then transition to IDLE mode followed by GO mode and then back to IDLE. The IDLE mode is where the safety operator of the ATMA is in control of the vehicle instead of the autonomous system. The GO mode is where the follower is operating autonomously. An exception to this is when a special software build was used to collect the data for the human performance of the scenario, not available in IDLE mode. In that case, the safety driver is in control of the system at all times, although the data was collected as if the system is operating autonomously.

3.3 Emergency Stop (E-Stop)

When an error condition occurred or when an E-Stop button was pressed, the follower vehicle would initiate an E-Stop procedure. There are two types of E-Stops: external and internal. An external E-Stop can be engaged by pressing one of the E-Stop buttons available inside and outside the follower vehicle. An external E-Stop applies full braking and kills the engine. An internal E-Stop is engaged when the E-Stop button on the leader is pressed, when an error is detected, or when an obstacle is detected by the follower's radar. The internal E-Stop applies full braking but does not kill the engine.

4.0 LOG FILE FORMAT

The follower vehicle log file is formatted as a comma separated value (CSV) file format. A new log file is created using a time stamp as the file name when the system is power cycled. Following is a sample log file:

```
# mpak follower log file
21:42:38.836,LDR,TYPE,CRUMB,STAMP,LAT,LON,ALT,HEADING,VELOCITY
21:42:38.837,FLW,CRUMB,STAMP,LAT,LON,ALT,HEADING,HDG(Desired),VELOCITY,VEL(Desired),GAP,GAP(Desir
ed),#SATS,VALID,CTE,THROTTLE,BRAKE,STEER,STATE
21:42:40.012,LDR,STAT_REQ
21:42:40.412,LDR,STAT_REQ
21:42:40.832,LDR,STAT_REQ
21:42:41.232,LDR,STAT_REQ
21:42:41.611,LDR,STAT_REQ
21:42:42.031,LDR,STAT_REQ
21:42:42.412,LDR,STAT_REQ
```

```
21:42:42.811,LDR,STAT_REQ
21:42:43.232,LDR,STAT_REQ
21:42:43.632,LDR,STAT_REQ
21:42:44.012,LDR,STAT_REQ
21:42:44.073,FLW,    0, 78164.450,  40.59367312,-105.14418347,1560.205, 177.630,   0.000, 322.81,
0.00,   0.00,   0.00, 15, 1, 0.000,   0.0,   0.0,   0.0, IDLE
21:42:44.173,FLW,    0, 78164.550,  40.59367312,-105.14418345,1560.205, 177.670,   0.000,   0.03,
0.00,   0.00,   0.00, 15, 1, 0.000,   0.0,   0.0,   0.0, IDLE
21:42:44.273,FLW,    0, 78164.650,  40.59367313,-105.14418345,1560.206, 177.670,   0.000,   0.04,
0.00,   0.00,   0.00, 15, 1, 0.000,   0.0,   0.0,   0.0, IDLE
21:42:44.373,FLW,    0, 78164.750,  40.59367313,-105.14418345,1560.206, 177.650,   0.000,   0.00,
0.00,   0.00,   0.00, 15, 1, 0.000,   0.0,   0.0,   0.0, IDLE
21:42:44.432,LDR,STAT_REQ
21:42:44.473,FLW,    0, 78164.850,  40.59367313,-105.14418347,1560.203, 177.660,   0.000,   0.03,
0.00,   0.00,   0.00, 15, 1, 0.000,   0.0,   0.0,   0.0, IDLE
21:42:44.573,FLW,    0, 78164.950,  40.59367313,-105.14418347,1560.204, 177.680,   0.000,   0.00,
0.00,   0.00,   0.00, 15, 1, 0.000,   0.0,   0.0,   0.0, IDLE
21:42:44.672,FLW,    0, 78165.050,  40.59367318,-105.14418355,1560.194, 177.650,   0.000,   0.20,
0.00,   0.00,   0.00, 19, 1, 0.000,   0.0,   0.0,   0.0, IDLE
21:42:44.772,FLW,    0, 78165.150,  40.59367320,-105.14418355,1560.193, 177.670,   0.000,   0.04,
0.00,   0.00,   0.00, 19, 1, 0.000,   0.0,   0.0,   0.0, IDLE
21:42:44.832,LDR,STAT_REQ
21:42:44.872,FLW,    0, 78165.250,  40.59367318,-105.14418355,1560.193, 177.630,   0.000,   0.04,
0.00,   0.00,   0.00, 15, 1, 0.000,   0.0,   0.0,   0.0, IDLE
21:42:44.972,FLW,    0, 78165.350,  40.59367318,-105.14418355,1560.193, 177.640,   0.000,   0.00,
0.00,   0.00,   0.00, 15, 1, 0.000,   0.0,   0.0,   0.0, IDLE
21:42:45.073,FLW,    0, 78165.450,  40.59367317,-105.14418355,1560.198, 177.660,   0.000,   0.04,
0.00,   0.00,   0.00, 15, 1, 0.000,   0.0,   0.0,   0.0, IDLE
21:42:45.173,FLW,    0, 78165.550,  40.59367317,-105.14418355,1560.198, 177.660,   0.000,   0.00,
0.00,   0.00,   0.00, 15, 1, 0.000,   0.0,   0.0,   0.0, IDLE
21:42:45.212,LDR,STAT_REQ
```

The file begins with the description as "# mpak follower log file" followed by the leader log entry header and the follower log entry header.

4.1 Leader log messages

The log data for the leader can vary based on the current operating mode.

IDLE MODE:

"21:42:42.811, LDR, STAT_REQ" All columns are divided by commas.

- 1st column contains the Time Stamp
- 2nd column indicates that it is a leader message
- 3rd column indicates that it is a status request message type

Note: The status request messages stop coming in when the leader is switched to GO

Once the leader starts moving in GO mode, the eCrumb data is generated by the follower's GPS system using relative the position of the leader. However, the follower records the eCrumb data as a leader message.

GO MODE:

21:44:3.011, LDR, ECRUMB, 0, 78243.300, 40.59346043, -105.14416280, 0.000, 0.000, 0.00

- 1st column contains the Time Stamp
- 2nd column indicates that it is a leader message
- 3rd column indicates the message type as an eCrumb message
- 4th column is the eCrumb Identification (ID). The eCrumb IDs are unique for each GO mode session. The eCrumb IDs are useful in figuring out which eCrumb the follower is heading towards at any given time.
- 5th column indicates the GPS time stamp data for that eCrumb
- 6th column indicates the position in Latitude
- 7th column indicates the position in Longitude
- 8th column indicates the altitude
- 9th column indicates the heading
- 10th column indicates the velocity of the leader at the eCrumb position in kilometer per hour

Note: The leader switches back to sending status request messages when the leader system returned to IDLE.

4.2 Follower log messages

Follower log message columns are described by the header.

21:42:38.837, FLW, CRUMB, STAMP, LAT, LON, ALT, HEADING, HDG(Desired), VELOCITY, VEL(Desired), GAP, GAP(Desired), #SATS, VALID, CTE, THROTTLE, BRAKE, STEER, STATE

- 1st column is the log timestamp
- 2nd column is the follower message type indicator
- 3rd column indicates the eCumb ID of the eCrumb that the follower is heading towards
- 4th column indicates the GPS timestamp for the follower message
- 5th column indicates the Followers position in Latitude
- 6th column indicates the Followers position in Longitude
- 7th column indicates the Followers Altitude
- 8th column indicates the Followers current heading
- 9th column indicates the Followers desired heading
- 10th column indicates the Followers current velocity
- 11th column indicates the Followers desired velocity
- 12th column indicates the Followers current GAP
- 13th column indicates the Followers desired GAP
- 14th column indicates the number of GPS Satellites the Follower is using
- 15th column indicates if GPS is valid
- 16th column indicates the Followers cross track error from its intended path
- 17th column indicates the current throttle command
- 18th column indicates the current brake command
- 19th column indicates the current steering command
- 20th column indicates the follower vehicles state (IDLE, READY, ROLLOUT, GO, and ESTOP)

Note: The follower algorithm may skip eCrumbs which do not contribute to a significant steering output. Because eCrumbs are generated only in GO mode, metrics such as desired velocity, gap values, and cross track errors are not available in IDLE and ROLLOUT modes.

5.0 TEST RESULT INTERPRETATIONS

Select portions of the collected log files were used to interpret the following results.

5.1 Tools used for analysis

- split_leader_follower.py: To filter the log files to leader or follower only logs. This script is necessary to prepare the original logs for plotting.
- csv_to_kml.py: To convert log files to leader and follower paths in keyhole markup language (KML). The KML output files can be used with Google Earth to view paths travelled by leader and follower.
- excel: To plot data for analysis. All charts were plotted using x-y scatter charts. For dual axis data with different scale, secondary axis is used to demonstrate the relationship. Time is always used as x-axis. The time values are in minute:second.one tenth of a second. For example, 20:13.5 on x-axis indicates the data occurred at 20th minute of the hour and 13.5 seconds.

5.2 Leader In-Cab E-Stops

The Leader vehicle contains an E-Stop button with the capability of stopping the Follower vehicle when the Follower is operating autonomously. The capability was tested by operating autonomously at a steady speeds of 7mph and 15mph, then pressing the E-Stop button in the Leader vehicle. The time to stop and stopping distance was measured for each of these speeds.

Log files used:

- 2017-06-27_15-10-48_log_CDOT_ESTOP_7MPH_TEST1_flw
- 2017-06-27_15-27-41_log_CDOT_ESTOP_7MPH_TEST2_flw
- 2017-06-27_15-35-03_log_CDOT_ESTOP_7MPH_TEST3_flw

The following three plots are the 7mph runs, showing time vs the speed in miles per hour (vertical).

For all three 7mph runs, the deceleration rate on E-Stop is around 5.5 seconds from the time E-Stop message was received.

Figure 1 Leader in Cab E-Stop – Run 1

Figure 2 Leader in Cab E-Stop – Run 2

Figure 3 Leader in Cab E-Stop – Run 3

During this test sequence, stopping distance was measured using a measuring wheel. Table 1 shows the stopping distance for both the 7mph and 15mph runs.

Target Speed	7 mph	15 mph
Stopping Distance	No data	68 ft. (20.7 m)
	40 ft. (12.2 m)	73 ft. (22.3 m)
	45 ft. (13.7 m)	80 ft. (24.4 m)

Table 1 Leader in Cab Estop Stopping Distance

5.3 Follower In-Cab E-Stops

The Follower vehicle contains an E-Stop button with the capability of stopping the Follower vehicle when it is operating autonomously. The capability was tested by operating autonomously at a steady speed (7mph and 15mph), then pressing the E-Stop button in the Follower vehicle. The stopping distance was measured for each of these test cases.

Stopping distance was measured using a measuring wheel. Table 2 shows the stopping distance for both the 7mph and 15mph runs.

Target Speed	**7 mph**	**15 mph**
Stopping Distance	13 ft (4.0 m)	28 ft (8.5 m)
	11 ft (3.4 m)	29 ft (8.8 m)
	9 ft (2.7 m)	24 ft (7.3 m)

Table 2 Follower in Cab E-Stop Stopping Distances

5.4 Follower External E-Stops

The Follower vehicle contains three external E-Stop buttons with the capability of stopping the Follower vehicle when the Follower is operating autonomously. The capability was tested by operating autonomously at a steady speed of 5mph, then pressing the each of the E-Stop buttons on the exterior of the Follower vehicle. The stopping distance was measured for each of these test cases.

Stopping distance was measured using a measuring wheel. The following table shows the stopping distance for each of the three E-Stops during the 5mph runs.

	Stopping Distance	**Lead Vehicle Speed**
Driver Side Button	5 ft (1.5 m)	4.8 mph
Passenger Side Button	6 ft (1.8 m)	4.7 mph
Front Button	5 ft (1.5 m)	4.6 mph

Table 3 Follower External E-Stop Stopping Distance

5.5 Human Driver Stopping Times

The time to stop the Follower vehicle, including human driver reaction time, was measured in this test. The test consisted of measuring the time for a human driver to respond to a "stop" command and bring the Follower vehicle to a complete stop. These tests were run in IDLE mode. The data in Table 4 was taken with the passenger telling the human driver when to stop and timing from his command to the vehicle coming to a complete stop.

Target Speed	7 mph	15 mph
Stopping Time (Including reaction time)	Discarded due to timing error	
	1.4 s	1.8 s
	0.9 s	1.7 s
	1.2 s	1.7 s
	1.4 s	1.1 s

Table 4 Human Driver Stopping Times (Follower)

5.6 Follow Distance Change under Hard Braking

The distance the GAP changes when the Leader brakes hard was measured to determine a minimum safe following distance. GAP measurements were taken at steady state right before Leader breaking and again when the vehicles came to a stop. Table 5 contains the data for both the 7mph and 15mph runs.

Target Speed	7 mph			15 mph		
Parameter	***Before***	***After***	***Change***	***Before***	***After***	***Change***
Follow Distance	80 m	76 m	4 m	83 m	59 m	24 m
	86 m	67 m	19 m	87 m	60 m	27 m
	83 m	65 m	18 m	81 m	52 m	29 m
	103 m	85 m	18 m			
	89 m	71 m	18 m			
	83 m	65 m	18 m			

Table 5 Follow Distance Change / Leader Hard Braking

5.7 U-Turn (65 foot radius)

A test was attempted to turn the Follower in less than the 100 foot radius defined in the specification (customer desired a tighter turn radius). The turn radius attempted was approximately 65 feet. During the turn, the Follower rejected some e-crumbs due to the turn radius and initiated its E-Stop sequence. The data was analyzed and it was determined that changing the wheel base to the correct wheel base for the truck coupled with changing the minimum e-crumb look ahead distance could improve the Followers ability to navigate tight turns. This will be changed and tested later in the validation event.

5.8 Driver Takeover

The Driver Takeover test was designed to measure the time it takes a human safety driver to switch from Autonomous mode to Manual mode and bring the vehicle to a safe stop. The test was performed with the passenger calling out a "Stop" command and the safety driver switching the system to "Idle" and applying the brakes to bring the vehicle to a stop as quickly as possible in a safe manner. Table 6 shows the times for both the 7mph and 15mph runs.

Target Speed	**7 mph**	**15 mph**
Stopping Time (Including reaction time and time to flip to manual mode)	2.0 s	2.2 s
	0.9 s	2.9 s
	1.7 s	1.5 s

Table 6 Driver Take Over Time

5.9 Obstacle Detection

The obstacle detection testing was conducted by dropping a barrel in the path of the follower, right behind the leader. The E-Stop sequence was initiated by the radar once the object was detected. Both the GAP distance to the object when first detected and the GAP distance to the object once the vehicle came to a complete stop were measured.

Following is an Electronically Scanning Radar (ESR) detection message.

```
21:18:25.910, ESR, RADAR, ESTOP, 53, 33.7, -2.1, 1.16324, 40.599759198, -
105.144562414, 40.600061376, -105.144591361, 1, 2
```

- 1st column is the timestamp

- 2nd column indicates it is an ESR message
- 3rd column indicates it is a Radar Message
- 4th column indicates it will be used for E-STOP
- 5th column is the Object Identification ID used by the radar for tracking
- 6th column is the Object range in meters
- 7th column is the Object angle in degree. The center is 0 degree. To the left are negative values. To the right are positive values.
- 8th column is the Object distance from the eCrumb that was used for detecting the obstacle. This value is configured using the web page.
- 9th column is the Radar position in Latitude
- 10th column is the Radar position in Longitude
- 11th column is the Object position in Latitude
- 12th column is the Object position in Longitude
- 13th column is the Object Status (1 = new target detected by radar, 2 = new updated target by radar, 3 = updated target)
- 14th column is the Range Mode (1 = Medium Range Update, 2 = Long Range Update, 3 = Both)

Table 7 contains the data taken at both the 7mph and 15mph runs for the stopping distance.

Target Speed	**7 mph**		**15 mph**	
Parameter	***Detection Range***	***Remaining Distance to Obstacle After Stop***	***Detection Range***	***Remaining Distance to Obstacle After Stop***
	46 m	125 ft (38 m)	50 m	72 ft (22 m)
	49 m	127 ft (39 m)	46 m	61 ft (19 m)
	45 m	104 ft (32 m)	44 m	52 ft (16 m)

Table 7 Obstacle Detection Stopping Distances

5.10 Adjusting Follow Distance

Following distance tests were done to compare the ability of the Autonomous system to hold a fixed GAP as compared to a human driver. On all of the following X-Y plots, the speed is plotted in orange and the gap is plotted in blue. The primary Y-axis on the left is for gap value in meters. The secondary Y-axis on the right is for speed in mph.

Please note that the gap values are measured between the leader's GPS antenna to the follower's GPS antenna. Therefore, the distance from leader's antenna to the rear bumper and the distance of follower's front bumper to follower's GPS antenna should be added for the desired gap for comparison. In our testing those values are 5.49 meter and 3.4 meter respectively. So, that equals 38.89 meters (30 meters) and 68.89 meters (60 meters) in the logs.

Figures 4 and 5 compare the system versus human GAP keeping at 7mph, 38 meters. The plot showed that the human driver did a fairly good job of holding the GAP, but had to make corrections more often.

Figure 4 GAP Test, System (7mph, 39 meters)

Figure 5 GAP Test, Human (7mph, 39 meters)

Figures 6 and 7 compare the system versus human GAP keeping at 15mph, 38 meters. The plot showed that the human driver did a fairly good job of holding the GAP, but had to make corrections more often.

Note: The big dip in gap control at 23:25.3 is due to missing leader eCrumbs for a few seconds due to GPS error causing incorrect calculation of the gap value. This affected the speed dipping below 12 mph to the right.

Figure 6 GAP Test, System (15mph, 39 meters)

Figure 7 GAP Test, Human (15mph, 39 meters)

Figures 8 and 9 compare the system versus human GAP keeping at 7mph, 69 meters. The plot showed that the human driver did a poor job of holding the GAP. This is due to the fact that human depth perception decreases with increased distance.

Figure 8 GAP Test, System (7mph, 69 meters)

Figure 9 GAP Test, Human (7mph, 69 meters)

Figures 10 and 11 compare the system versus human GAP keeping at 15mph, 69 meters. The plot showed that the human driver did a poor job of holding the GAP. This is due to the fact that human depth perception decreases with increased distance.

Figure 18 GAP Test, System (15mph, 69 meters)

Figure 19 GAP Test, Human (15mph, 69 meters)

5.11 Lane Accuracy, Straight Line

Straight line accuracy tests were performed using cones to form a lane. The leader vehicle then drove the lane and the Follower accuracy was measured by visually inspecting that no cones were hit, and by plotting the cross track error (CTE) during the run.

Three lane widths were used. The first lane width was 130 inches from base to base between the cones. This width was ran at speeds of 7mph and 15mph. During both runs, no cones were hit.

The second lane width was 115 inches from base to base between the cones. This width was ran at speeds of 7mph and 15mph. During both runs, no cones were hit.

The third lane width was 112.5 inches from base to base between the cones. This was the lower limit due to the width of the vehicle and the desired following accuracy (± 4”). This width was ran at speeds of 7mph and 15mph. During both runs, no cones were hit. During this run, data was plotted (Figure 12 and 13) of the cross track error. On the 7mph run, the CTE stayed within ± 1.6 inches. On the 15mph run, the CTE stayed within ± 3.1 inches.

Figure 12 Lane Accuracy, CTE, 7mph

Figure 13 Lane Accuracy, CTE, 15mph

5.12 Lane Accuracy, Cornering

Cornering lane accuracy testing was done by painting a line around a 100 foot radius, 90 degree corner. The Leader drove the corner, keeping close to the painted line, but no closer than 4 inches. The Follower was observed as it went around the corner to ensure that it did not touch the line at any point. During early testing at 15mph, we had some GPS issues (damaged cable). Once the cable was corrected, the testing was completed. Three runs were done at 7mph and 3 runs were done at 15mph. During each of these runs, the Follower tracked the corner without touching the painted line. Data was taken from the log files to see what happened to cross track error during this test. Plots of the cross track error for 7mph and 15mph runs are shown in Figures 14 and 15 respectively. The cross track errors are plotted in blue and the speed is plotted in orange. The cross track errors in the 7mph run show about a 3 inch bias to the right and a variance of ± 2.75 inches. The cross track errors in the 15mph run show about a 12.5 inch bias to the right and a variance of ± 4 inches. More testing will have to be done to see if the bias was due to vehicle inertia or antenna bias (placement of antennas).

Figure 14 Lane Accuracy, Corner, 7mph

Figure 15 Lane Accuracy, Corner, 15mph

5.13 Tight Turn Situation

Turn radius testing was done on the north end of the runway. The turn radius tested varied from approximately 55 – 60 ft. Turn speeds were maintained between 5 – 7 mph. Five circles of the pad were performed with no incident. Upon attempting tighter turn, vehicle e-stopped due to throwing out e-crumb for being too close, and then being unable to maneuver to next e-crumb. A sample of the turn data is presented in Figure 16.

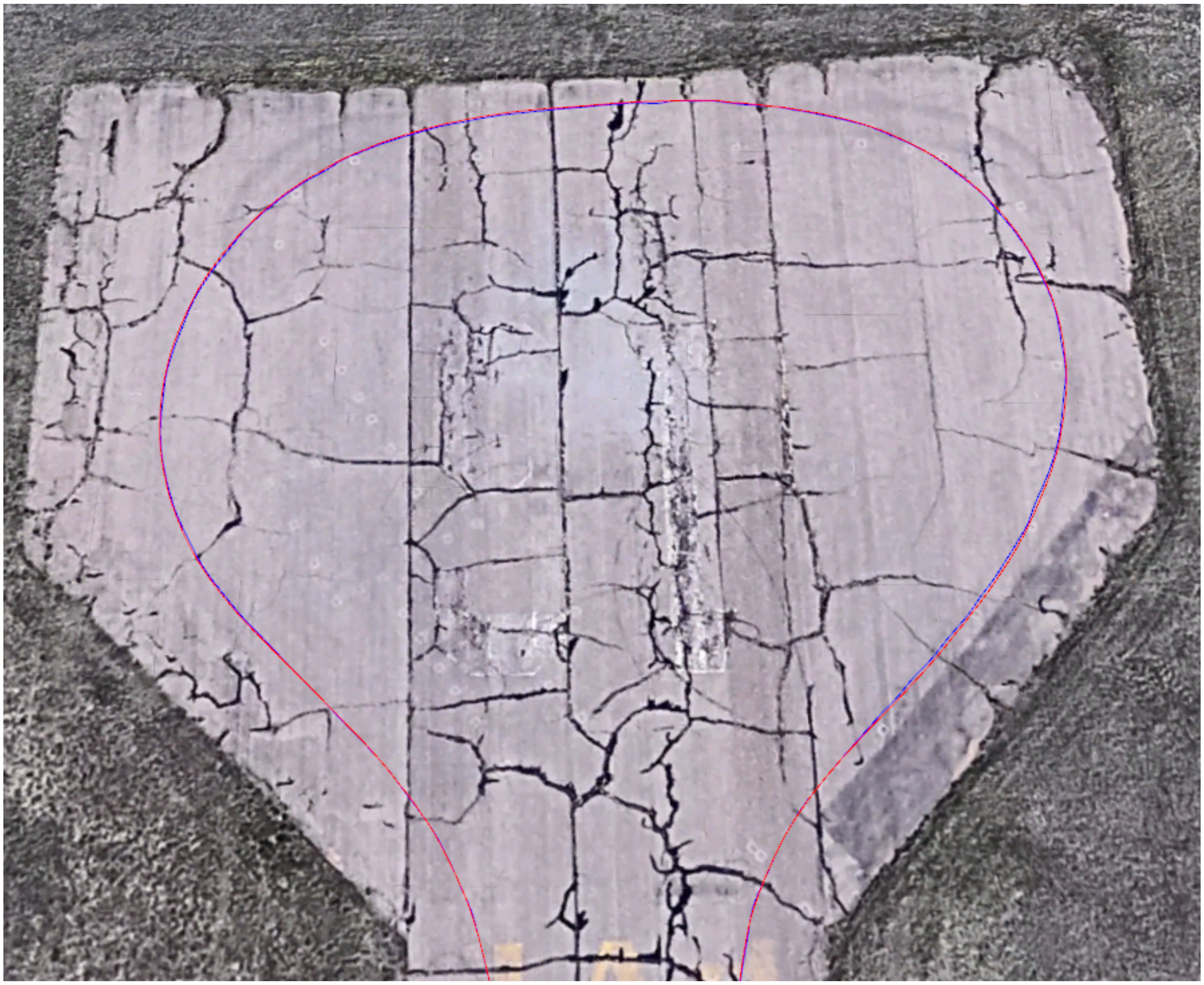

Figure 16 Tight Turn Testing

5.14 Acceleration

The acceleration testing was done by having the leader accelerate from a stop to 15 mph as fast as they could and then maintain 15 mph until follow distance stabilized, to characterize effect of hard acceleration on follow distance. After the first run, we kept both systems in "go" and accelerated from a full stop to 15 mph for remaining two runs. A stable follow distance seemed to be reached quickly, no issues seen. See Figure 17 for System run.

Repeated with a human driver, no issues were seen, unable to tell qualitatively what the difference in time to reach stable follow distance is. See Figure 18 for Human Driver run.

The gap distance is plotted using blue. The orange line is for speed (velocity). In this test, both M-PAK and human driver accelerates to 15 mph and comes to a stop when the gap value between the leader and follower stabilized. The tests were repeated three times (Figure 17 and Figure 18).

Figure 17 Acceleration test, System

Figure 18 Acceleration Test, Human Driver

5.15 Max Speed Exceeded

This test was omitted because maximum following speed is a future capability.

5.16 Parking Brake Set in Follower

One test was performed with parking brake engaged in follower vehicle. Upon rollout, follower did not move but advanced throttle to 100% in an attempt to match the leader. Results were as expected.

5.17 Communications Loss

The communications loss test was performed by driving in a straight line at 7 mph. When the Leader and Follower vehicles reached a steady 7 mph, the lead vehicle system was switched off. This caused the Follower lose communications with the Leader and eventually run out of e-crumbs to follow. The Follower continued until it reached the last transmitted e-crumb, and then turned hard left or right and e-stopped itself. The turn was dependent on what the last corrective action was before reaching the last e-crumb. Performed three times with same results each time. This behavior will be fixed in the next release of software.

5.18 GPS Loss

The GPS loss test was performed by driving in a straight line at 7 mph. When the Leader and Follower vehicles reached a steady 7 mph, the GPS connector was removed from the Leader. This caused the Leader to lose GPS and stop sending updated position information to the Follower. The Follower continued until it reached the last transmitted e-crumb, and then turned hard left or right and e-stopped itself. The turn was dependent on what the last corrective action was before reaching the last e-crumb. Performed three times with same results each time. This behavior will be fixed in the next release of software.

5.19 Bump Steer

The first run used a 4x4, on a straightaway, outside the lane of cones. No change in driving behavior was noted when the Follower ran over the 4x4. The second run used a 6x6, but the radar e-stop was triggered before 6x6 was run over.

Next, we found suitable pothole on the runway, ~6 in deep. We ran two tests over pothole. Small steering correction of follower was observed when rear tires hit pothole. However, the follower stayed on course. It is suspected that body roll moving the GPS antenna was more responsible for this than the pothole's bump steer effect.

We then moved to lane of cones. We used the 4x4 as bump. The Follower stayed in lane while crossing over the bump, no issues were noted.

We checked bump steer over the 4x4 while cornering. We placed the bump on the inside wheel and then on the outside wheel for a second run. No issues were noted during either run.

5.20 Slalom Course

A slalom course was set up by placing cones 100' apart. We ran 2 runs at 7 mph and 1 at 15 mph. One 7 mph run was performed with the Scorpion unit deployed. With scorpion down one cone was brushed but none knocked over. Otherwise no issues were noted during the slalom course. The cross track error for the three runs are plotted in Figure 19, Figure 20, and Figure 21. The cross track error is plotted in blue and the speed is plotted in orange. The slalom data shows cross track errors approaching 6 inches during the dynamic parts of the turns.

Figure 19 Slalom Run 1, 7mph

Figure 20 Slalom Run 2, 7mph

Figure 21 Slalom Run 3, 12mph

5.21 E-Stop from Leader in Corner

We performed this test twice at 7 mph. The first test showed that the follower stopped within path of corner. During the second test the follower strayed outside of corner during e-stop. This behavior is dependent on steering angle at time of e-stop. This behavior will be fixed in the next revision of the software. We elected to have follower continue following e-crumbs during an e-stop event to avoid straying from the lead vehicles path while stopping.

5.22 Obstacle Detection in Corner

The current radar limitations will not allow an obstacle to be detected around a corner.

6.0 CONCLUSION

The charts plotted from the log files give some insights into the behavior of the M-PAK. For example, E-Stop from the leader's cab is slower compared to external E-Stops and human driver. The gap control of the M-PAK is much better and a lot more consistent compared to the human driver gap control, especially for larger gaps such as 60 meter. Higher speed also increases the range gap values. Most of the time, cross track errors are under acceptable range. However, bumpy road and unreliable or inaccurate GPS data may lead to much larger cross track errors.