Enhancing School Zone Safety: Case Studies in Puerto Rico using Driving Simulation

SAFETY RESEARCH USING SIMULATION
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List of Acronyms

AADT	Average annual daily traffic
AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of variance
CARE	Crash Analysis Reporting Environment
EPDO	Equivalent property damage only
FHWA	Federal Highway Administration
HSM	Highway Safety Manual
ISA	Internet Scene Assembler
MUTCD	Manual on Uniform Traffic Control Devices
NHS	National Highway System
NHTSA	National Highway Transportation Safety Administration
PCR	Pedestrian crossing the road
PDO	Property damage only
PR-2	Puerto Rico Highway #2
PRDTPW	Puerto Rico Department of Transportation and Public Works
PRHDM	Puerto Rico Highway Design Manual
RTI	Real Time Technologies
SRTS	Safe Routes to School
TCD	Traffic control device
TOD	Time of day
UPRM	University of Puerto Rico at Mayagüez
UTC	University Transportation Center
VMT	Vehicle miles traveled
VRU	Vulnerable road user
WHO	World Health Organization

Units Conversion

Unit	Equivalence
1 km	1000 m
1 ft	0.3048 m
1 mile	1.609 km

1 Introduction

Highway safety is of paramount importance in a technological era when cities are implementing smart features and smart mobility is gaining momentum. Our current cities are striving to become livable communities that accommodate all users of the transportation system [1]. Drivers and pedestrians coexist in urban environments that were developed to maximize motorized mobility. In terms of school zones, the interaction of drivers and pedestrians is critical, with additional issues related to the possibility of distracted children crossing the streets [2] and drivers speeding along the school zones [3].

The intricacies of motor vehicles and pedestrian interaction generate dangerous situations for children in and around school zones. Statistics show that there is a significant safety problem in school zones. There are five teenager pedestrian fatalities every week in the United States and an increase of 13% in the pedestrian fatality rate of 12- to 19-year-olds since 2013 [2]. Contributory factors to this fatality rate include distracted walking, unsafe street crossing, unsafe drop-off or pick up zones, and poor signalization delimiting the school zone area [2]. A study conducted at two school zones in Mayagüez, Puerto Rico, showed that 89% of the students did not use the marked pedestrian crosswalk in front of the school to cross the road [4]. The pedestrian behavior observed in this study presents risky actions from the student population.

Vulnerable road users (VRUs) are road users that, due to the lack of outside shield protection, sustain a higher risk of injury in case of a collision, namely pedestrians and bicyclists. Some road users can be considered to be more vulnerable than others, such as the elderly, the disabled, and children. According to the World Health Organization (WHO), pedestrians and bicyclists are a factor in 26% of all road-related fatalities worldwide [5]. The National Highway Traffic Safety Administration (NHTSA) indicates that pedestrian and bicyclist fatalities accounted for 18.2% of the 37,461 highway-related fatalities in the United States in 2016 [6]. There is a need for new traffic safety strategies that, along with law enforcement, engineering measures, and educational safety programs, will continue reducing and preventing deaths of VRUs in our transportation system.

In Puerto Rico, various schools are in the vicinity of urban arterial roads with high traffic (over 20,000 vehicles per day, or vpd) and posted speed limits over 40 mph. Spot speed studies conducted at 19 schools located in the western region of Puerto Rico showed low driver compliance with the speed limits in more than half of the school zones studied [7, 8]. This type of driver behavior increases the risk of crashes. Safety programs, such as the Federal Highway Administration (FHWA) initiative Safe Routes to School (SRTS), have been developed to improve accessibility and safety around schools. After the implementation of the SRTS initiative in 18 states, reductions of 14% in injury risk and 13% in fatality risk were achieved for pedestrians and cyclists, respectively [9].

Driving simulators are cost-effective tools that allow the evaluation and analysis of driver performance when implementing emerging technologies, helping in the understanding human factors related to road safety without putting human lives at risk [10, 11]. This report presents the results of an operational and safety analysis to evaluate driver behavior in and around two school zones using the driving simulator of the University of Puerto Rico at Mayagüez (UPRM).

The objective of this research was to evaluate driver behavior when approaching a school zone and the effectiveness of a new combination of road signage and pavement markings. The strategy behind the use of new traffic control devices (TCDs) in the driving simulator was to evaluate their effectiveness in controlling drivers' speeds. Two school zones located in the western region of Puerto Rico were used in a driving simulation experiment to compare the drivers' performance in existing conditions and a new TCD configuration. A survey was conducted to explore drivers' level of knowledge about TCDs in school zones to assist in the development of the simulation scenarios.

2 Literature Review

The literature review associated with this research project and its relationship with highway safety is presented in five sections: school zones, signage and pavement markings, speed limit compliance, vulnerable road users, and driving simulators.

2.1 School Zones

According to the *Manual on Uniform Traffic Control Devices* (MUTCD) developed by the FHWA, a school zone is a designated roadway segment approaching, adjacent to, and beyond school buildings or grounds or along the area where school activities occur [12]. The school zones area varies by state and territory. In Puerto Rico, the *Puerto Rico Highway Design Manual* (PRHDM) demarks a school zone “by painting a yellow line 30 cm. wide at a distance of fifty (50) meters from both sides of the entrance to a school adjacent to a street or highway” [13]. Nevertheless, they all include school signage at the beginning of the school zone and the end of the school zone. In the same way, the speed limit in the school zone varies by state and territory and even varies between different types of roads. According to the MUTCD, these speed limits are recommended, but not required. The definition and area of the school zone merit consideration since a study performed in Texas found that extended school zones do not result in lower speeds for a longer distance. Speeds increased approximately 0.9 mph for every 500 ft of school zone length [14].

2.2 Signage and Pavement Markings

The MUTCD states that if a school zone area is designated under state or local statute, an S1-1 school zone sign (a pentagon sign with two persons inside) shall be installed at the beginning of the zone and an S5-2 (end school zone) shall be installed at the end of the school zone [12]. The S1-1 sign has an optional complementary sign that indicates a school zone is ahead. It also may include an arrow and the distance to entering this zone. The school zone speed limit sign or the S5-1 are considered as support in the MUTCD, specifically to standardize signage for the school zone areas. For pavement marking, the MUTCD incorporates the word “SCHOOL” as an option for the designer. For this reason, there is not a regulatory sign or pavement marking that shall be placed in every school zone. Every state or territory has the discretion to implement the sign and/or pavement marking combination most suitable for the existing geometric and operational conditions in the school area. The MUTCD changed the sign background color from yellow to fluorescent green to make drivers more aware of the presence of the school zone area [12].

This discretion deviates from the uniformity essence of the MUTCD, resulting in different sign and pavement marking configurations in every state. For example, in North Carolina, flashing beacons have been placed on school zone signs, and results showed that there is no practical difference in vehicle speeds between the flasher and no-flasher locations during school hours [14]. Also, in North Carolina, it was found that "Your Speed" signs result in a significant reduction in speed from 3.0 mph to 4.5 mph over a 12-month post-installation period [3]. On the other hand, a study conducted by Schrader found that the speed-monitoring displays reduced speed by an average of 5.1 mph in the short term and a total of 3.6 mph in the long term [16]. A study performed in Illinois explored the effects of five school zone TCDs (fiberoptic signs, span wire-mounted flashing yellow beacons, post-mounted flashing yellow beacons, transverse lavender stripes, and large painted legends), each at a unique site. From these countermeasures, only the site with the fiber-optic signs experienced a significant speed reduction at the 95 percent confidence level [17].

2.3 Speed Limit Compliance

Speeding in school zones is a significant and sensitive safety issue. The consequences of speeding in school zones make it particularly important that additional resources are allocated to reducing speeding [18]. Researchers have concluded that the safety of a school zone requires not only the use of effective signage and strict enforcement but also the establishment of reasonable school zone speed limits [19]. Ash suggests that a combination of effective TCDs, public education, and appropriate law enforcement are necessary to improve speed-limit compliance in school zones [20]. González performed speed spot studies to evaluate compliance in 13 schools in the western region of Puerto Rico and found that the average speed of drivers was higher than the posted school speed limit and that in none of the schools was compliance met [7].

2.4 Vulnerable Road Users

The influence of several roadway factors on VRUs' crash-related injuries and severity have been studied. Crash data shows that pedestrians are 2.7 times more likely to be involved in a crash in an urban segment than cyclists; nevertheless, pedestrians were found to have a 77% lower crash probability than bicyclists in good weather conditions [21]. Crashes involving cyclists are concentrated in the afternoon peak, whereas pedestrian crashes have peak times during morning, lunch, and afternoon periods [21]. Other studies have found that roads with speed limits above 35 mph, dark lighting conditions, and curves may significantly increase the probability of evident injury for pedestrians [22, 23]. In addition, positive relationships between pedestrian fatalities and traffic density have been identified for non-access-controlled principal and minor arterial urban roads [24]. Other factors, such as intersections, non-illuminated roadways, and pedestrians between 24 and 64 years old, increase the probability of a severe injury in major urban arterials; while having no traffic control, three-lane roadways, and pedestrians less than 12 years old increase the probability of severe injury in minor urban arterials [25].

2.5 Driving Simulators

Driving simulators are commonly used for research experiments, particularly for studies to improve operation and safety. Simulation is an invaluable research tool because it eliminates a great deal of the risk associated with evaluating driving tasks in the real world. In addition, it helps to expedite data collection and reduce costs related to the construction of experimental scenarios [26].

Driving simulators offer various advantages compared to observing traffic conditions in the real world. According to several authors, such as De Winter et al. and Fisher et al., there are multiple advantages that could be associated with the use of driving simulation: controllability and reproducibility of scenarios, ease of data collection, reduction of physical risk while experimenting in driving conditions, and opportunity for immediate feedback and instruction [10, 27].

The controllability and reproducibility of scenarios in driving simulation allows researchers to manage traffic in the simulation, control environmental conditions, and manipulate the road layout in order to meet the performance analysis goals of the research. The ease of data collection provides a more accurate and effective measurement of the performance in the simulation. The reduction of physical risk while experimenting in driving conditions is another safety related benefit. Also, the possibility of getting feedback during and after simulations gives researchers an opportunity to modify the scenarios in order to improve the effectiveness of the study and propose more accurate solutions.

However, driving simulators have some disadvantages and challenges that need to be faced, including: limited physical and behavioral fidelity, few investigations that demonstrate if skills learned in driving simulation transfer to the road, and the possibility of simulation sickness [10, 27].

The findings of previous studies that evaluated the behavioral validity of driving simulators found simulators to be valid tools for assessing a variety of driving measures, including speed, lateral position, braking response, inattention, and risky driving behaviors [28]. For example, a research study was conducted to evaluate various schemes of signage and pavement markings for two different types of school zones using a driving simulator. The results obtained by evaluating average speed, relative speed difference, standard deviation of acceleration, and 85th percentile speed showed that flashing beacons and “school ahead” warning devices on the roadside were recommended for schools adjacent to multilane roadways [11].

3 Methodology

The methodology developed for this research project consists of four major sections: school selection process, description of school zones selected, online survey, and driving simulator experiments.

3.1 School Selection Process

Four primary steps were followed during the school selection process: (1) evaluation of crash history, (2) screening process, (3) site selection, and (4) interviews of school zone stakeholders. A brief description of each step follows.

- *Evaluation of crash history:* A review of the crash history from the years 2014 to 2016 in 20 school zones in western Puerto Rico was carried out, making use of the Crash Analysis Reporting Environment (CARE) database made available by the Puerto Rico Department of Transportation and Public Works (PRDTPW). Variables like crash type, collision type, presence of VRUs, day of the week, and roadway characteristics were considered in this section.
- *Screening process:* A screening process was performed based on a combination of Highway Safety Manual fundamentals and the application of engineering judgment. The focus population was established at the beginning of the research: school zones with the potential to reduce the numbers of crashes. The information of crashes by type and total numbers were considered to calculate the equivalent property damage only (EPDO) average crash frequency, to characterize each of the school zones, and to obtain a ranked list of alternative selections. The *Highway Safety Manual* (HSM) assigns a weight of 542 to fatalities, 11 to injury crashes, and 1 to property damage only (PDO) to calculate this performance measure [29]. Table 3.1 presents the total EPDO score for each school.

Table 3.1 – EPDO scores

School	Crash Type			EPDO
	PDO	Injury	Fatal	
Rafael Martinez Nadal	102	15	0	267
Maria D. Faria	37	8	1	667
S.U. Samuel Adams	26	6	0	92
Conrado Rodriguez	36	11	0	157
S.U. Mildred Arroyo	15	6	1	623
Eladio Tirado Lopez	16	5	0	71
Franklin D. Roosevelt	215	54	2	1893

- *Site Inspections:* Applying concepts from road safety audits, site inspections complemented with Google Maps Street View were carried out at the seven schools that passed the screening process. General information was gathered for each school, including characteristics related to the signage around the school area, pavement markings and sidewalks, the students' drop-off/pick-up dynamics, roadway geometry, faculty parking availability, and pavement condition, among others.
- *Interviews:* Interviews of school directors, teachers, parents, and road users were conducted. These interviews included questions related to their perception of safety in the school zones, the condition of the roadway infrastructure, and speeds that drivers used to travel through this area. There were also questions about the modes of transportation used by students to get to school and the aspects that could be changed to improve the safety around the school zones.

A final ranking was developed including the following variables: exposure, EPDO, environment complexity, and interviews. The exposure was measured using an estimate of the vehicle miles traveled (VMT) for each segment of the schools, as shown in Table 3.2; schools with lower exposure were ranked higher. For the EPDO, the first place was assigned to the school with the highest EPDO score and the last place to the school with the lowest EPDO score. The complexity of the environment refers to the information that was gathered from various sources, including site inspections and virtual tours using Google Maps Street View, and schools that reflected a greater sense of safety were ranked higher. The interviews were ranked considering the information provided; schools that reflected a greater sense of safety for their school community were ranked higher.

Table 3.2 - Exposure

School	AADT	Length (mi)	Exposure (VMT per day)
Rafael Martinez Nadal	10,306	0.4	4,130
Maria D. Faria	21,229	0.4	8,492
S.U. Samuel Adams	42,947	0.57	24,480
Conrado Rodriguez	26,674	0.6	16,004
S.U. Mildred Arroyo	5,824	0.65	3,786
Eladio Tirado Lopez	8,570	0.49	4,199
Franklin D. Roosevelt	77,314	0.6	46,388

Table 3.3 presents the score assigned by the research team to each of the variables considered for the selection process. The final score is calculated as a sum of the rankings for all the

variables. The selected road segment to conduct the simulation experiments represented the two sites with the lowest ranking scores: Franklin D. Roosevelt and Second Unit (S.U.) Samuel Adams.

Table 3.3 – School zone ranking

School	Exposure	EPDO	Environment Complexity	Interviews	Total
Rafael Martinez Nadal	6	4	5	5	20
Maria D. Faria	4	2	6	3	15
S.U. Samuel Adams	2	6	1	1	**10**
Conrado Rodriguez	3	5	4	6	18
S.U. Mildred Arroyo	7	3	7	7	24
Eladio Tirado Lopez	5	7	3	4	19
Franklin D. Roosevelt	1	1	2	2	**6**

3.2 Description of School Zones Selected

Two schools were selected to carry out a more in-depth study: S.U. Samuel Adams and Franklin D. Roosevelt.

The first school selected was S.U. Samuel Adams, which is located in the municipality of Aguadilla, in an area is classifies as rural. It provides education from pre-kinder to 9th grade and has a student enrollment of 900. Figure 3.1 shows a view of the area where the school is located, marking the school with a square and a pedestrian bridge with an oval.

Figure 3.1 - S.U. Samuel Adams. Source: Adapted from Google Maps

This school has direct access from the arterial highway PR-2. In this section, the highway has two lanes in each direction and a posted speed limit of 45 mph. As mentioned earlier, this is a rural area, and there are some segments without sidewalks. There is a pedestrian bridge with ramps in front of the school to connect the school with its surrounding area. Also, the two directions of PR-2 are separated by a New Jersey barrier that has a 5-ft-tall fence on top to eliminate the possibility for pedestrians to cross the street at that point and force them to use the bridge.

Inside the school, there is a drop-off area that is not used as expected. According to the interviews, the designated drop-off area is not convenient for parents with small children because they have to walk their children to the classroom. Therefore, parents park their cars on the shoulder of PR-2.

The findings of the site inspection showed that the speed limit and school zone signs had not been updated to the colors indicated in the last version of the MUTCD. Also, it was found that there were lines to delimit the beginning and end of the school zone, but no pavement marking with the word "School."

Furthermore, the main problem found in this school zone is the long line of vehicles that is formed by parents waiting to drop off or pick up their children. In addition, once the child is inside the vehicle, each driver must maneuver, reversing onto the right lane of the arterial street or unexpectedly merging onto the arterial from the shoulder. All these maneuvers create additional congestion and deteriorate the safety for all users.

The second school selected was Franklin D. Roosevelt, located in the municipality of Mayaguez, in an area classified as urban. It provides education from kinder to 6th grade and has a student enrollment of 165. Figure 3.2 shows a view of the area where the school is located, marking the school with a square and a pedestrian bridge with an oval.

Figure 3.2 - Franklin D. Roosevelt. Source: Adapted from Google Maps

This school serves two communities that are separated by the arterial street PR-2. This six-lane arterial highway has a posted speed of limit 40 mph. Near the school, there is a pedestrian bridge with no ramps, and the nearest signalized intersection to this bridge is approximately a quarter of a mile away. The entrance to the school is on Dr. Vadi Street, which is parallel to PR-2.

The site inspection conducted at this school showed that the signage and the pavement markings related to the school zone were deficient. Also, findings of the interviews indicate that the pedestrian profile includes children, elderly, and mothers with their babies in strollers. Therefore, it is very difficult for them to use the stairs step pedestrian bridge. These pedestrians must go to the nearest intersection, cross PR-2 (which in this section has nine lanes and a total crosswalk length of 119-ft), walk to the school, and then use the same long route back home. In some cases, pedestrians cross under the bridge due to the long distance they must walk. Refer to Figure 3.3 for a plan view of the intersection of urban arterial PR-2 and Nenadich street.

Figure 3.3 - Plan view of the intersection PR-2 and Nenadich street. Source: Google Maps

3.3 Online Survey

A survey was conducted across the US and Puerto Rico to evaluate drivers' knowledge of school zone areas and how they behaved in school zones. The survey consisted of six sections: demographics, school transportation, school zone speed perception, school zone signage, signage and pavement markings combination, and pedestrian crosswalks. A total of 306 responses were recorded for the survey with a 90% confidence level and 5% margin of error. None of the questions were mandatory. For this reason, the total responses for each question may vary. Appendix A shows the questionnaire presented to the population surveyed.

3.4 Driving Simulator Experiments

This section includes a description of the equipment and its components, the procedures for the generation of scenarios, and the experimental designs of the school zones that were selected.

3.4.1 Equipment

The UPRM driving simulator consists of a desktop portable simulator with three main components: a driving cockpit, a visual display, and a computer system. The driving cockpit consists of a car seat, steering wheel, gear shifter, two turn signals, and acceleration and braking pedals. It is mounted on a wooden base with six wheels, making it applicable for performing ambulatory studies. The visual display consists of three overhead projectors and three screens that provide 120 degrees of road visibility at a resolution of 1024 x 768 pixels. The computer system uses a laptop and a desktop computer with Realtime Technologies Inc. (RTI) SimCreator/SimVista simulation software and an audio system capable of representing typical vehicle and ambient noises.

3.4.2 Base Scenario Development

A base scenario is developed for each school. These base scenarios are created by replicating the characteristics of the school zones to resemble the current condition, using tools and software such as Google Maps®, AutoCAD®, SketchUp®, Blender®, and ISA®. Initially, images are taken from Google Maps as a base to draw details in AutoCAD, including lines corresponding to lanes, pavement markings, and medians, among others. Then, this plan is processed with SketchUp where the 3-D environment is formally defined with the corresponding textures, color, and elevations; additional elements such as walls and bridges can also be included with SketchUp. In Blender, the file is converted into a file that can be read by ISA. Finally, in ISA the vegetation, buildings, signage, and all the animations of pedestrians walking, cars, and other details are added.

3.4.3 Experimental Design: S.U. Samuel Adams

The experimental scenarios are based upon a National Highway System (NHS) section of PR-2 in Aguadilla, Puerto Rico, adjacent to the S.U. Samuel Adams School. The road segment is 1.5 km long with a minimum 500 m before and after the school zone area. Figure 3.4 presents real and simulated images of the NHS section of PR-2.

A factorial design was used for this experiment with two blocks. The factorial is based on a 2x2x3 design with blockage. The three factors are traffic, the presence of pedestrians, and vehicles parked on shoulder. The blockage variable is the signage and pavement marking configurations. These variables will be discussed in later sections.

Figure 3.4 – Existing roadway vs. simulated road – Samuel Adams

The experimental scenarios considered four main variables: traffic flow, pedestrian presence, vehicles parked on shoulder, and signage and pavement marking configurations. The traffic flow variable has two levels (no vehicles and moderate vehicles), the pedestrian presence variable has three levels (no pedestrians, children, and adults with children), and the vehicles parked on shoulder variable has two levels (no vehicles and vehicles). The blockage is by configuration. Configuration 1 includes the current signage and pavement marking whereas Configuration 2 has the recommended signage and pavement markings. The signage and pavement marking configuration variable has two levels: current road configuration and proposed road configuration.

Table 3.4 shows detailed information on the 24 scenarios.

A total of 36 subjects participated in the driving simulator experiments. Eighteen subjects were assigned to each configuration balanced by age and gender, with 50% female, 50% male, and 33% in each age group (18-24, 25-45, and 46-70 years old).

Table 3.4 - Experimental scenarios for S.U. Samuel Adams

Scenario	Signage Configuration	Pedestrians	Vehicles in the Shoulder	Traffic
1	Actual	Kids and Adults	Yes	Yes
2	Actual	Kids and Adults	Yes	No
3	Actual	Kids and Adults	No	Yes
4	Actual	Kids and Adults	No	No
5	Actual	None	Yes	Yes
6	Actual	None	Yes	No
7	Actual	None	No	Yes
8	Actual	None	No	No
9	Actual	Only Kids	Yes	Yes
10	Actual	Only Kids	Yes	No
11	Actual	Only Kids	No	Yes
12	Actual	Only Kids	No	No
13	Proposed	Kids and Adults	Yes	Yes
14	Proposed	Kids and Adults	Yes	No
15	Proposed	Kids and Adults	No	Yes
16	Proposed	Kids and Adults	No	No

17	Proposed	None	Yes	Yes
18	Proposed	None	Yes	No
19	Proposed	None	No	Yes
20	Proposed	None	No	No
21	Proposed	Only Kids	Yes	Yes
22	Proposed	Only Kids	Yes	No
23	Proposed	Only Kids	No	Yes
24	Proposed	Only Kids	No	No

3.4.4 Experimental Design: Franklin D. Roosevelt

A factorial design with blocking was used for this experiment. Two factors were considered: time of day (TOD) and pedestrian crossing the road (PCR). The TOD variable has two levels: day and night. The PCR variable has three levels: no pedestrian crossing the road, a pedestrian crossing from the median to the shoulder (from left to right), and a pedestrian crossing from the shoulder to the median (from right to left). All scenarios had other pedestrians walking along the sidewalk or the median to establish the presence of pedestrians along the corridor.

A spot speed study was conducted in the selected road segment. Two hundred free-flow speed observations were collected during a typical weekday morning. The 85th percentile of the observed speeds was 53 mph, while the mean speed was 46 mph. The 85^{th}-percentile speed was used to program the simulation when to start the pedestrian crossing maneuver. The roadway crossing maneuver and trajectory of the pedestrian was programed so that if a user drove at or near the 85^{th}-percentile speed (53 mph), the driver would encounter the pedestrian close to the middle of the center lane of the PR-2 arterial highway, therefore creating a potential conflict. This pedestrian was going to or coming from a minor street that serves as access to the school ground.

The blocking variable is signage configuration. Configuration 1 reflects the existing road signs, and Configuration 2 reflects the existing signs with the addition of an overhead advanced warning sign with flashing beacons.

Table 3.5 shows the variable combinations for the twelve scenarios (six for each configuration).

The experimental scenarios are based upon a segment of the urban arterial highway PR-2 northbound located between kilometers 156.1 and 155.1. This road section has a typical cross section that includes three 12-ft lanes in each direction, a variable median, a sidewalk on the left side, a variable paved shoulder on the right side (next to the school), and a posted speed limit of 40 mph. Figure 3.5 presents the existing roadway cross section and the simulated scenario.

Table 3.5 - Experimental scenarios for Franklin D. Roosevelt

Scenario	Signage Configuration	Time of Day	Pedestrian Crossing the Road
1	Actual	Day	Right to left
2	Actual	Day	Left to right
3	Actual	Day	None
4	Actual	Night	Right to left
5	Actual	Night	Left to right
6	Actual	Night	None
7	Proposed	Day	Right to left
8	Proposed	Day	Left to right
9	Proposed	Day	None
10	Proposed	Night	Right to left
11	Proposed	Night	Left to right
12	Proposed	Night	None

Figure 3.5 – Existing roadway vs. simulated scenario – Franklin D. Roosevelt

A total of 24 subjects participated in the experiment. Twelve subjects were assigned to each configuration, with 50% female, 50% male, and 33% in each age group (18-24, 25-45, and 46-70 years old).

The following research hypotheses were tested:

I. Participants driving through scenarios with the advanced warning sign exhibit lower speeds than those driving in scenarios with the current road signage conditions.

II. The presence of the advanced warning sign contributes to a greater speed reduction (i.e., drivers are more aware) when drivers meet the pedestrian crossing the road.

4 Online Survey

The online survey developed for his study had six sections. The first requested demographic information, the second addressed school transportation, with questions about access to facilities, school types, involvement in crashes, and mode of transportation to school, and the third covered school zone speed perception in urban and rural scenarios. The fourth section assessed subjects’ understanding of school zone signage, the fifth asked which combination of signage and pavement makings best reflected their understanding of the school zone and its speed limits, and the sixth asked which signage combination best reflected the presence of pedestrian crosswalks.

4.1 Demographics

The demographics section inquired about subjects’ age, gender, and the state or territory where they drove most often. It also asked participants if they drove through a school zone on their daily commute. The gender distribution was 39.7% males and 60.3% females, and the age distribution was 18-25 years (26%), 26-40 years (32%), and 41-75 years (42%). See Table 4.1 for details.

Table 4.1 - Gender and age distributions

Age Group	Female (%)	Male (%)
18 - 25	15	11
26 - 40	17	15
41 - 75	28	14

The state and territory distribution can be seen in

Table 4.2. Puerto Rico and Florida were the states with the most responses, with 64.7% and 6.3%, respectively.

Table 4.2 - State and territory answer distributions

State	Subjects (%)	State	Subjects (%)
Arizona	1.3	Nevada	0.3
California	2.0	New Jersey	0.3
Colorado	0.7	New Mexico	0.3
Connecticut	0.7	North Carolina	0.7
Delaware	0.7	Ohio	0.7
Florida	6.3	Oklahoma	0.3
Georgia	0.7	Oregon	0.7
Hawaii	0.3	Puerto Rico	64.7
Idaho	0.3	Rhode Island	0.3
Illinois	0.3	South Dakota	0.7
Indiana	0.3	Tennessee	0.3
Iowa	3.6	Texas	1.7
Louisiana	2.6	Virginia	2.3
Maryland	2.3	Washington	0.7
Massachusetts	2.3	Wisconsin	1.0
Missouri	0.7		

4.2 School Transportation

In this section, 76 answers were recorded in response to questions about transporting school-age kids to and from school and which type of school they attended. For the question related to crashes when traveling to and from school, only 4% of those surveyed admitted being involved in a crash. It should be noted that this question did not directly address school zone crashes.

With regard to the designated pick-up and drop-off area, 25% of those surveyed said there was not a designated pick-up or drop-off area. This endangers school-age kids due to traffic exposure and related road dangers. Figure 4.1 presents a summary of the responses.

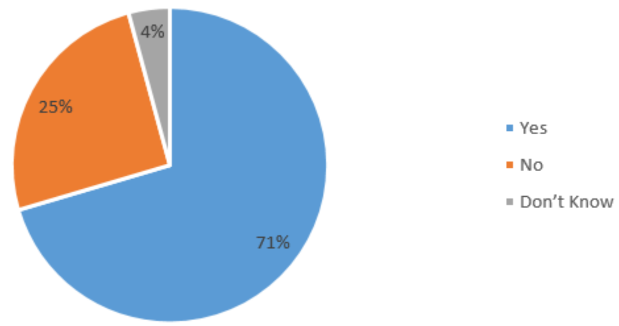

Figure 4.1 – Presence of a pick-up/drop-off area in school zones

4.3 School Zone Speed Perception

This section addressed drivers' knowledge of speed limits in school zones, their preferred travel speeds, and their perception about what should be a safe speed in these zones. Figure 4.2 presents the perceptions of those surveyed with regard to the effectiveness of speed limits at different school levels. There was a reduction in perceived effectiveness that corresponded to the increase in school level, likely due to the perception that older children are aware of road dangers.

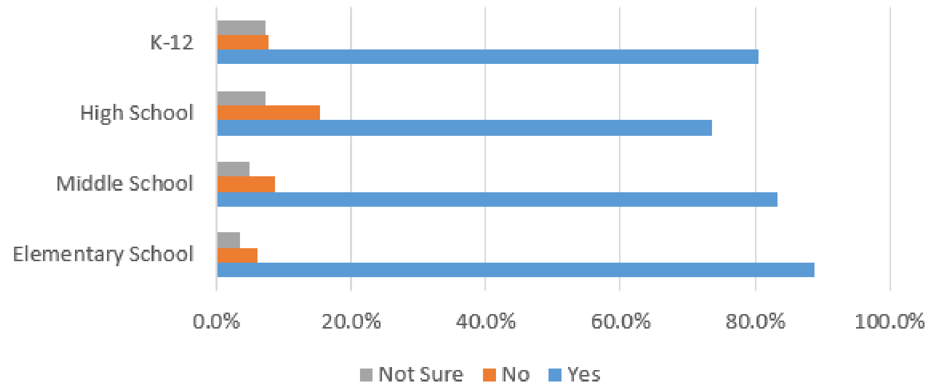

Figure 4.2 – Effectiveness of speed limit by school level

Participants indicated that they travel through school zones at speeds of 15 and 20 mph, but at least 45% indicated that the speed limit should be 20 mph or higher. This is of concern due to the speed-reduction problems in school zones when vehicles stop to drop off or pick up kids. The statutory speed limit varies for each state and territory, but 15 mph tends to be used often. A summary of the responses regarding speeds in school zones is presented in Figure 4.3.

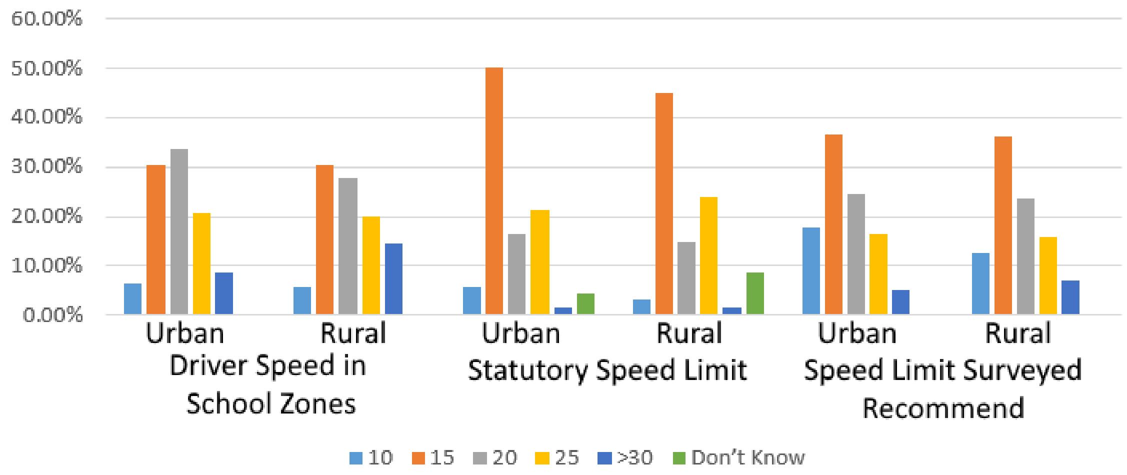

Figure 4.3 – Perception of speed limits

4.4 School Zone Signage

In this section, participants were asked what they understood from the signs shown in

Table 4.3. Just 48% of subjects correctly identified the School Zone sign. The Pedestrian Crosswalk sign was correctly identified by 97% of the subjects, and the School Crosswalk sign by 52%. A possible reason for the confusion about the School Zone sign is that the MUTCD has been changing the color from yellow to fluorescent green. For this reason, an educational campaign should be implemented to inform the community of signage modifications and their meanings. In Puerto Rico, a mixture of yellow and fluorescent green colors in signs is very common.

Table 4.3 - Pedestrian and school signage survey responses

Options	**Participants Responses per Roadway Sign (%)**		
	 **School Zone Sign (306)**	 **Pedestrian Crosswalk (306)**	 **School Crosswalk Sign (302)**
Pedestrian Crosswalk	16.99	97.06	21.85
School Zone	48.37	0.00	13.91
Family Crosswalk	8.50	0.00	8.61
School Crosswalk	24.84	0.06	52.32
Other	1.31	2.29	3.31

Note: The shaded cells correspond to the correct meaning of the sign.

4.5 Signage and Pavement Makings

Four different signage and pavement configurations, as shown in Figure 4.4, were presented in the survey. The participants were asked to rank from 1 to 4 the combination that they thought gave the most useful information to the driver. These combinations included:

- Pavement marking before the school zone with the word “SCHOOL,” or no pavement marking.
- A green school sign or a yellow school sign.
- An overhead sign with flashing beacon including the school speed limit, or a roadside sign with the school speed limit.
- An end of school zone sign, or an end of school zone sign with yellow pavement marking.

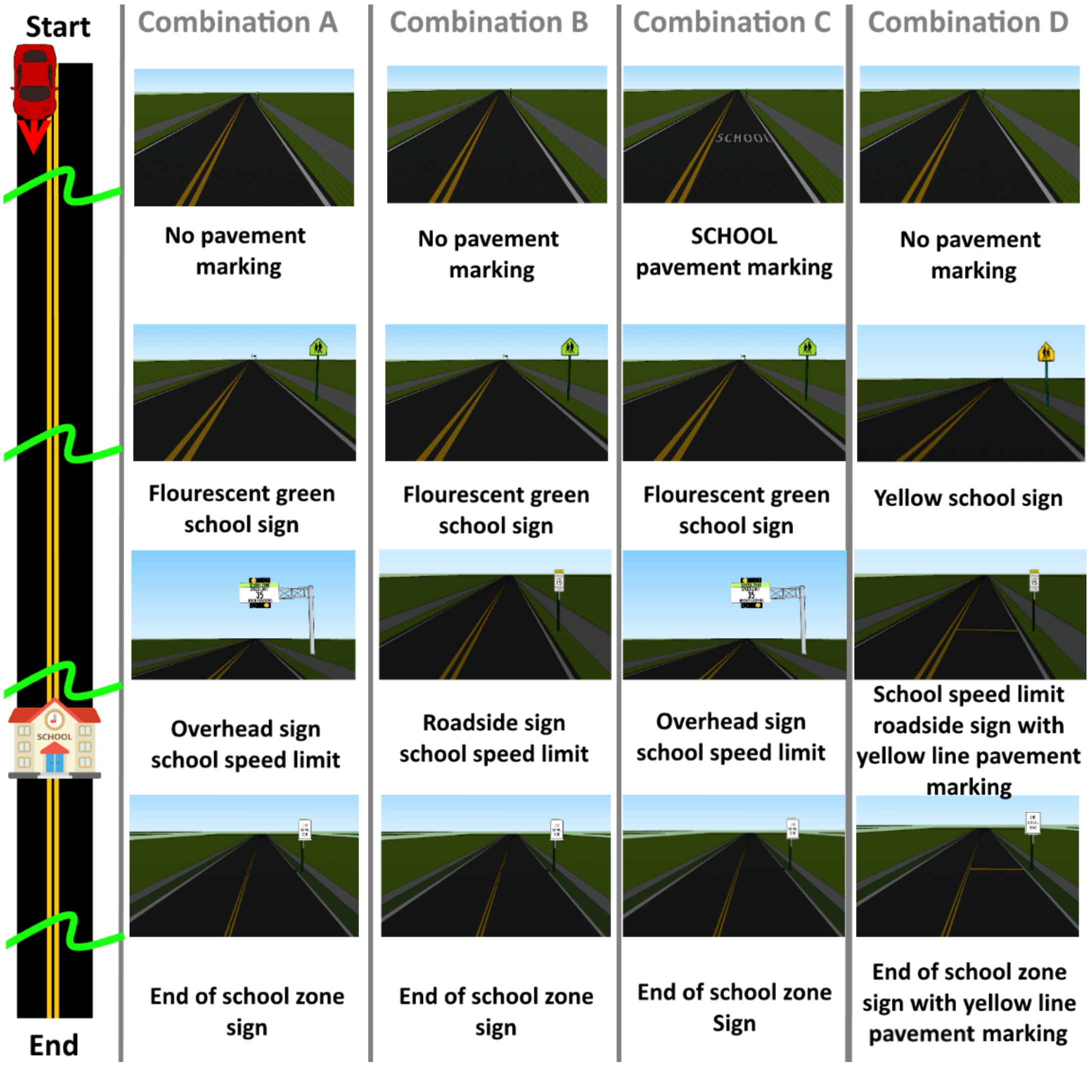

Figure 4.4 - Combinations of signage and pavement markings

The survey results indicated that Combination C was considered the most informative for 73% of the surveyed subjects. This combination includes the “SCHOOL” pavement marking, a green school sign, an overhead sign with the school speed limit, and an end of school zone sign. The second most informative was Combination A for 46% of the surveyed subjects. This combination also includes the green school sign, an overhead sign with the school speed limit, and the end of school zone sign. It does not include the “SCHOOL” pavement marking. The least informative were Combinations B and D. These combinations do not have an overhead sign with the school speed limit; instead, they have a roadside sign with the school speed limit. The total responses for this question are shown in Figure 4.5.

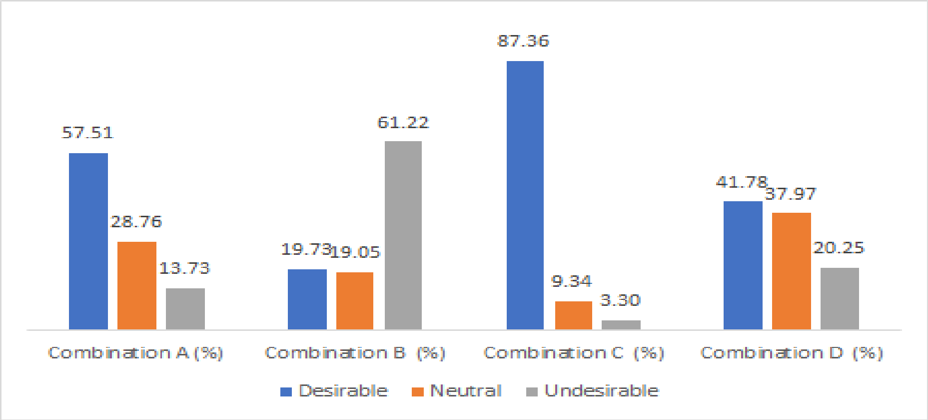

Figure 4.5 - Stated preferences for the combination of traffic control devices

4.6 Pedestrian Crosswalks

Four alternative sign configurations for pedestrian crosswalks were presented with the following question: “How effective do you think are the following signs in informing drivers to identify the presence of a crosswalk?” Five response options were given: extremely effective, slightly effective, neutral, slightly ineffective, and extremely ineffective. A total of 306 drivers responded the survey.

The two alternatives with the most “extremely effective” votes were a roadside sign with flashing beacons and a combination of an overhead sign plus a roadside sign. The results of these two are shown in Figure 4.6 and Figure 4.7 - Assessment of overhead and roadside signs.

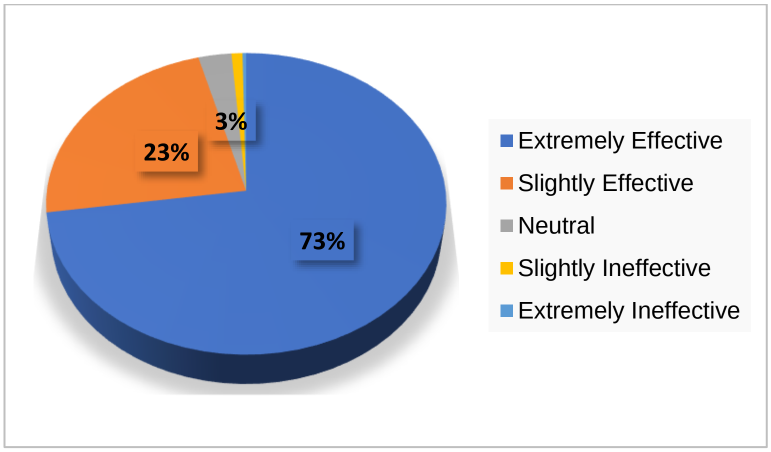

Figure 4.6 – Assessment of roadside sign with flashing beacons

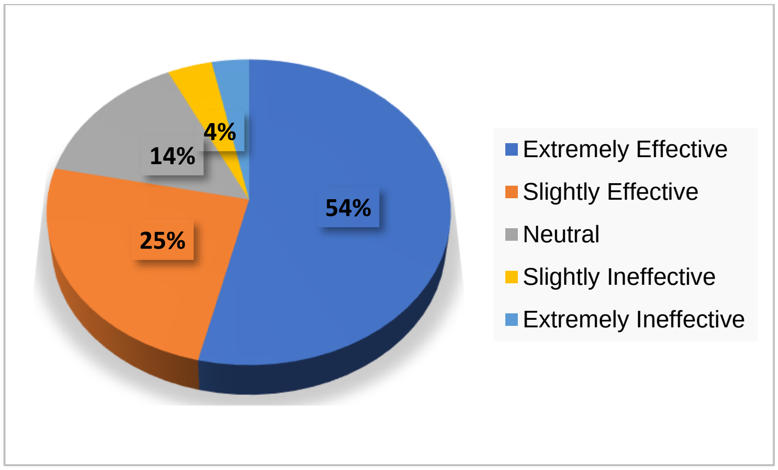

Figure 4.7 - Assessment of overhead and roadside signs

The characteristics from these two options were combined to generate the sign evaluated in the driving simulation experiments. The resulting sign corresponded to an advanced warning overhead sign with flashing beacons with the legend in Spanish "CRUCE DE PEATONES ADELANTE," which means "PEDESTRIAN CROSSING AHEAD." Figure 4.8 shows the advance warning sign with flashing beacons designed for the study.

Figure 4.8 - Overhead pedestrian warning sign with flashing beacons and the legend "CRUCE DE PEATONES ADELANTE"

5 Analysis of Driving Simulation Scenarios

The analysis of driving simulation scenarios was concentrated on the two selected school zones, S.U Samuel Adams and Franklin D. Roosevelt.

The S.U. Samuel Adams analysis emphasized the interaction between vehicles parked on the shoulder, vehicles traveling along the main travel lanes, and pedestrians on the sidewalk on a major high-speed suburban arterial.

The Franklin D. Roosevelt analysis focused on the interaction between pedestrians crossing at midblock and vehicles traveling along a high-speed, six-lane, divided urban arterial.

5.1 S.U. Samuel Adams

This section describes the criteria for generating the zones of interest and the response variables evaluated (mean speed, speed compliance, lateral position, and acceleration noise). A trajectory analysis and T-test compared the effects of the proposed combination of TCDs on driving behavior in the school zone.

5.1.1 Zones of Interest

Figure 5.1 shows the five zones of interest with their relative positions for each simulation scenario. Each zone had a different length depending on the situation and the configuration. Zone 0 is where the subjects traveled at free-flow speed before reaching the school zone in both configurations. Zone 1 is where the first TCD in the school zone was located. Zone 2 corresponds to the area between the first TCD and the school speed limit sign (roadside or overhead). Zone 3 corresponds to a location in the vicinity of the school driveway where a pedestrian may walk on the shoulder near the right travel lane toward oncoming traffic. Vehicles parked at an angle in the right shoulder were also present in this zone. Zone 4 represents the end of the school zone identified with the last TCD in each configuration. Figure 5.1 shows the roadway signs and pavement symbols in Spanish, following Puerto Rico's Design Directives.

The mean speed and the acceleration noise were the response variables obtained from the simulations. The mean speed was obtained for all subjects at each zone of interest. The acceleration noise was calculated as the standard deviation of the acceleration for all subjects at each zone of interest. In terms of outliers, one subject was removed from the data set because the driver exhibited irrational behavior through the simulation by continuously accelerating and exceeding 80 mph.

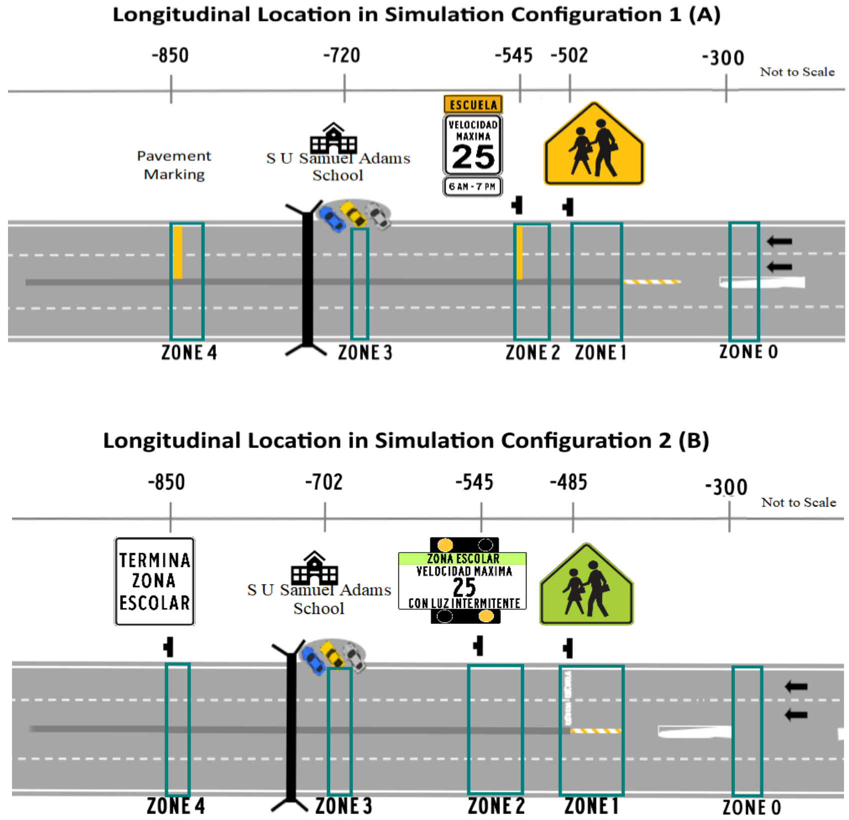

Figure 5.1 - Longitudinal position of zones of interest for each configuration

5.1.2 Mean Speed

A pairwise two-sample T-test was performed with a Bonferroni correction for all scenarios in each zone of interest in order to evaluate the difference in mean speed between Configurations 1 and 2. The results of the P-values of the T-test of the mean speed variable are summarized in Table 5.1. *All cells with an asterisk* correspond to the subjects in Configuration 2 that drove slower than in Configuration 1, representing 70.8% of the cells in the four zones. However, the differences in the mean speed between configurations in each zone of interest were not statistically significant. The cells in Zones 3 and 4 that are *shaded and marked with an asterisk* correspond to the drivers of Configuration 2 that achieved a mean speed of 27 mph or lower. In Configuration 1, Zone 3 of Scenario 1 reached the 27 mph speed or lower. This zone is shaded only.

Table 5.1 – T-test of the difference in mean speed for the zones of interest between Configurations 1 and 2

Scenario	Zones of Interest			
	1	2	3	4
1	0.967*	0.468	0.528	0.213
2	0.831*	0.218*	0.762*	0.454*

3	0.485*	0.408*	0.155*	0.271*
4	0.528	0.967	0.940	0.512
5	0.900*	0.992	0.377*	0.925*
6	0.219*	0.269*	0.596*	0.640
7	0.706*	0.808*	0.295*	0.654*
8	0.641*	0.543*	0.646	0.692
9	0.732*	0.412*	0.480*	0.885*
10	0.218*	0.089*	0.093*	0.177*
11	0.113	0.881	0.120*	0.333*
12	0.369*	0.555*	0.947	0.785*

Scenario 8 corresponded to a school zone without any observed activity. Drivers behaved in a similar manner in Zones 1 and 2 in both scenarios 2 and 8. Once the subjects realized that there were no pedestrians or parked vehicles Zones 3 and 4, they reacted by driving at higher speeds as compared to the existing condition. This behavior is similar to that found in inactive highway work zones when workers are not present and TCDs are still active. Furthermore, the driver reaction is a result of TCDs not conveying a clear message, as stated in the MUTCD.

Figure 5.2 compares the speed profiles for each subject for Configuration 1 and 2 of Scenario 10. Graphical representations comparing speeds in both configurations for all experimental scenarios are provided in Appendix B.

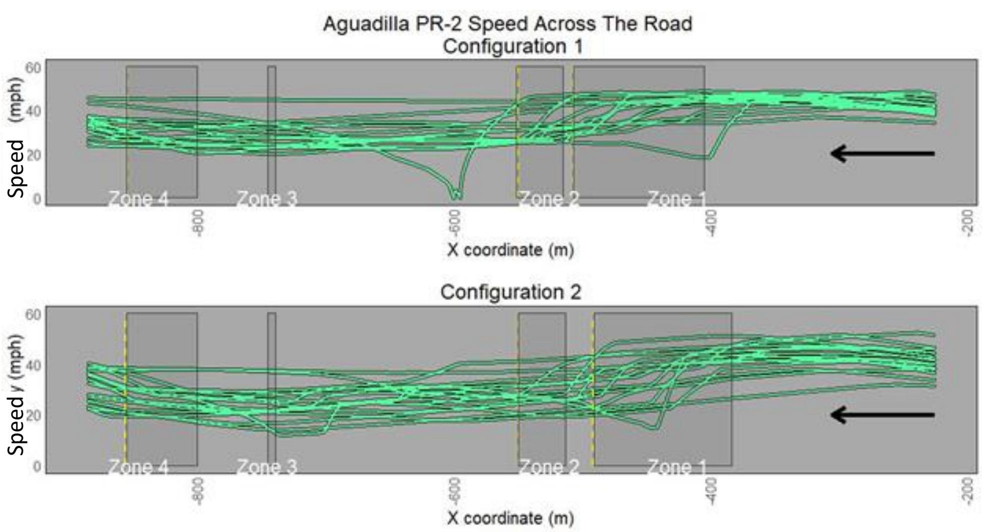

Figure 5.2 - Scenario 10 subjects' speed by configuration

5.1.3 Speed Limit Compliance

Table 5.2 shows speed limit compliance for Zones 0 and 3 for Configurations 1 and 2. Zone 0 corresponds to the free-flow conditions at the posted speed limit of 45 mph, and Zone 3 represents the area after the school speed limit sign where the highest activity and conflicts take place in the vicinity of the school driveway. The school speed limit was 25 mph.

Subjects in the scenarios with the existing configuration of TCDs had a speed limit compliance percentage between 40% and 73% in Zone 0. Inside the school zone (Zone 3), the speed compliance percentage decreased in all but Scenario 6. The speed compliance percentage in Zone 3 was between 13% and 53%. For the simulated scenarios with the new TCDs in place, the speed limit compliance percentage improved in 83% of the scenarios evaluated in Zone 3. The increase in compliance was from 2.9% to 30.4%. In Scenarios 1 and 8, there was a reduction in the speed limit compliance.

Table 5.2 - Speed compliance percentage between configurations

Scenario	Compliance (%)				Δ Compliance (%)
	Configuration 1		Configuration 2		Conf 2 – Conf 1
	Zone 0	Zone 3	Zone 0	Zone 3	Zone 3
1	60.00	46.67	62.50	43.75	-2.92
2	66.67	53.33	62.50	56.25	2.92
3	40.00	13.33	43.75	43.75	30.42
4	46.67	33.33	68.75	37.50	4.17
5	46.67	33.33	31.25	50.00	16.67
6	40.00	40.00	68.75	43.75	3.75
7	46.67	20.00	62.50	25.00	5.00
8	66.67	26.67	62.50	25.00	-1.67
9	60.00	33.33	62.50	56.25	22.93
10	66.67	46.67	62.50	56.25	9.58
11	53.33	40.00	68.75	43.75	3.75
12	73.33	53.33	81.25	56.25	2.92

5.1.4 Lateral Position

The P-value of the T-test for the mean position variable is shown in

Table 5.3. Three zones in Scenario 4 were statistically different; this difference is justified by the number of subjects in the left lane vs the right lane (see shaded cells). In Scenario 4 of Configuration 2, drivers tended to change to the left lane earlier, as shown in Figure 5.3. In Scenario 12, subjects in Configuration 1 stayed in the right lane most of the time, while in Configuration 2 they were split between lanes. This can be seen in Zones 3 and 4 of Scenario 12 in

Table 5.3. See Appendix C for roadway position graphs for all experimental scenarios.

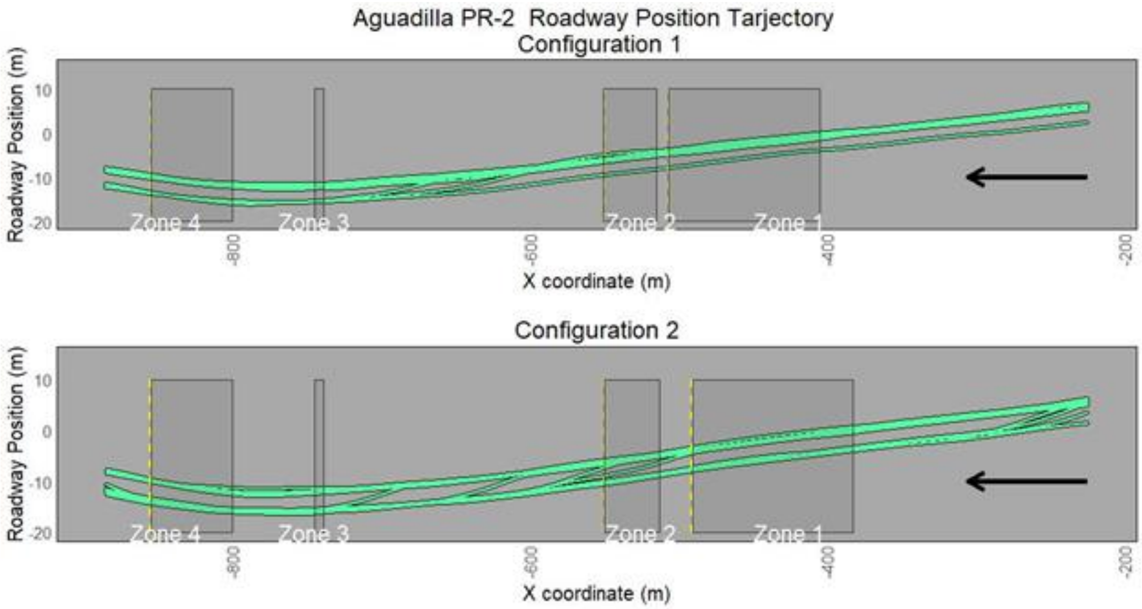

Figure 5.3 - Roadway position of subjects' trajectory for each configuration

Table 5.3 – T-test of lateral position for zones of interest

Scenario	Zones of Interest			
	1	2	3	4
1	0.814	0.130	0.094	0.096
2	0.652	0.385	0.632	0.735
3	0.987	0.168	0.168	0.168
4	0.706	0.015	0.023	0.024
5	0.406	0.830	0.956	0.833
6	0.885	0.490	0.595	0.778
7	0.908	0.160	0.311	0.348
8	0.913	0.071	0.053	0.046
9	0.617	0.546	0.575	0.645
10	0.128	0.706	0.924	0.928
11	0.690	0.176	0.058	0.056
12	0.558	0.081	0.048	0.042

Acceleration Noise

The P-value results of the pairwise T-test for acceleration noise are presented in Table 5.4. Note that there is a significant difference in acceleration for Scenarios 3, 5, and 10 in Zones 2 and 4 for Scenario 11. Zone 2 is where drivers are encouraged to change their speed from 45 mph to 25 mph because they are about to enter the school zone. For the three scenarios in Zone 2, subjects in Configuration 2 had a smaller change in acceleration, as did subjects who drove Scenario 11 of Configuration 1. A smaller change in acceleration is safer for road users since the change in velocity is smoother. Figure 5.4 shows the acceleration of subjects in Scenario 10 for both configurations. See Appendix D for graphical representations of subjects' acceleration in all experimental scenarios.

Table 5.4 – T-test of acceleration noise for zones of interest

Scenario	Zones of Interest			
	1	2	3	4
1	0.894	0.252	0.076	0.180
2	0.931	0.289	0.263	0.350
3	0.294	0.045	0.238	0.294
4	0.668	0.894	0.241	0.057
5	0.736	0.037	0.396	0.085
6	0.454	0.199	0.172	0.064
7	0.683	0.183	0.052	0.050
8	0.584	0.218	0.368	0.067
9	0.596	0.231	0.947	0.946
10	0.434	0.016	0.069	0.282
11	0.610	0.375	0.369	0.026
12	0.626	0.084	0.801	0.434

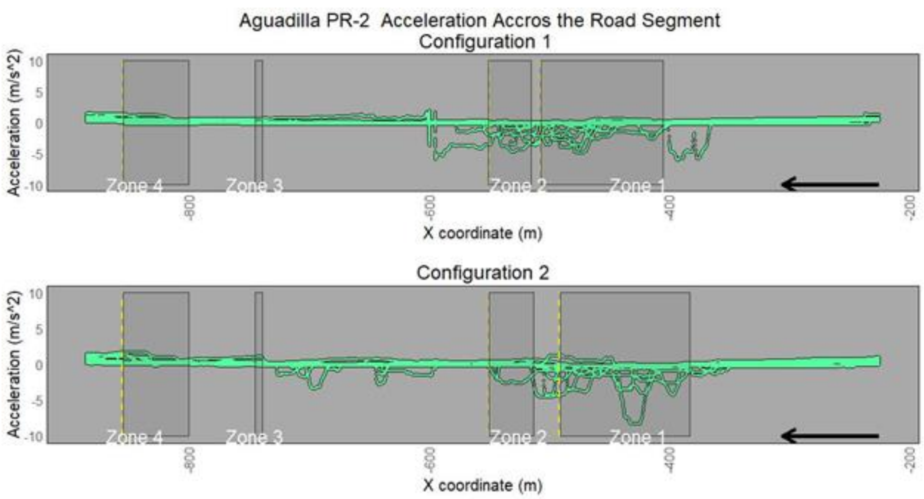

Figure 5.4 – Subjects' acceleration along the road trajectory

5.2 Franklin D. Roosevelt

The simulation evaluated the effect of the TCDs and the presence of a pedestrian on driver behavior. The mean speed and the standard deviation of speeds were used as response variables from the driving simulator. A statistical analysis was performed to evaluate the reaction to the presence of the pedestrian and to identify significant differences between the mean speeds at the different zones. Comparisons were made between the results obtained from the scenarios in Configuration 1 and Configuration 2.

5.2.1 Zones of Interest

Four zones of interest were defined along the roadway scenarios, as shown in Figure 5.5. Zone 1 is where drivers traveled at free-flow speeds before the message from the overhead sign (located at position -155 m) became readable. Zone 1 was located 250 m after the starting point of the simulation where drivers accelerated to reach their constant speed. Zone 2 was located after the overhead sign and before the area where the pedestrian crossed the road, allowing researchers to evaluate the possible influence of the sign on the driver's speed selection. Zone 3 began at the coordinate where drivers were able to see the pedestrian and allowed researchers to evaluate driver reaction to the pedestrian. Zone 4 began after the pedestrian trajectory and was useful in evaluating changes in driver behavior after the potential conflict.

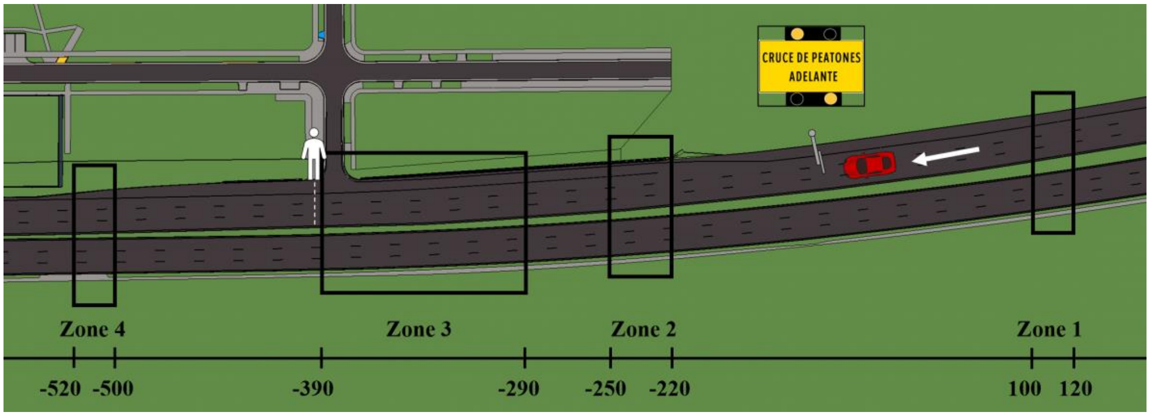

Figure 5.5 - Zones of interest near Franklin D. Roosevelt

5.2.2 Speed Selection along the Scenario

The speeds selected by subjects in each zone for all twelve scenarios were evaluated. Figure 5.6 shows the speed profiles of all subjects for Scenario 2 in Configurations 1 and 2 (the coordinates of the X-axis go from right to left). There are two apparent effects of the overhead advanced warning sign. First, the general dispersion shown in the speed profiles for Configuration 1 is higher than the dispersion of the speeds when the overhead sign is present. Second, half of the subject drivers reduced their speed by 25 mph or more before reaching the crossing pedestrian in Configuration 2 with the overhead sign, compared to 25% of subjects in Configuration 1. See Appendix F for graphical representations of drivers' speed selection for all experimental scenarios.

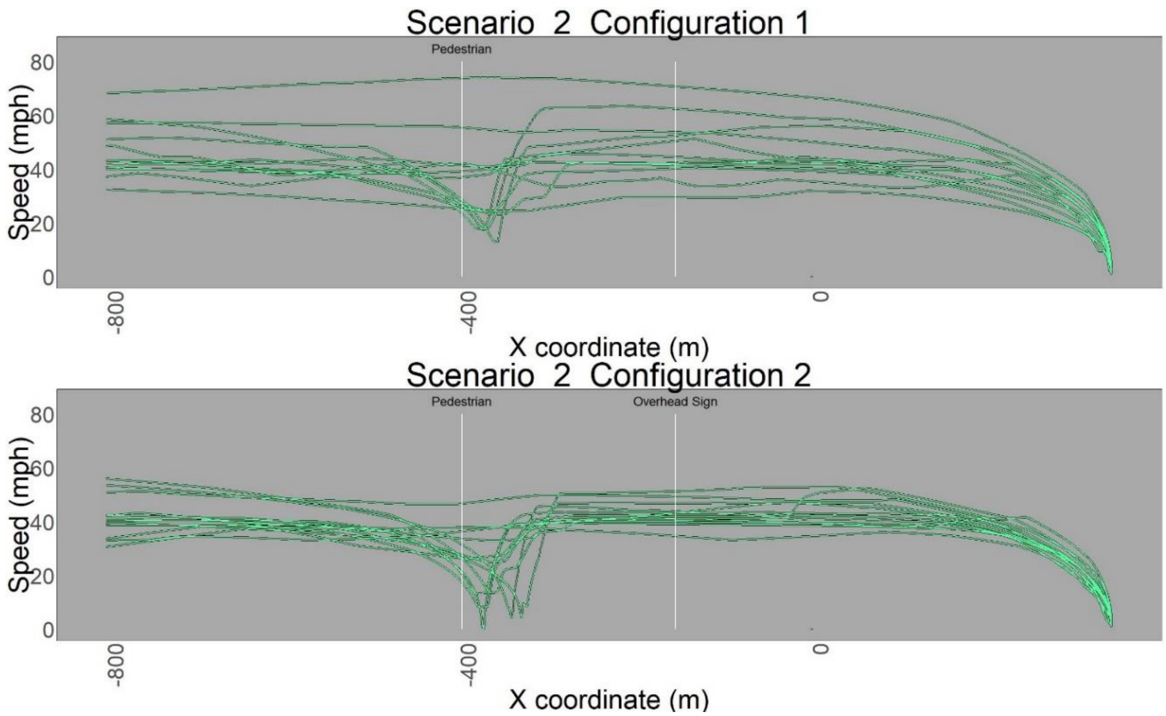

Figure 5.6 - Speed profiles of Scenario 2 for Configurations 1 and 2

Table 5.5 presents the results of the comparison analysis of the mean speeds using an ANOVA with Bonferroni correction and the results of the analysis of the standard deviation of mean speeds using a non-parametric analysis. The comparison was made between the base scenario (Configuration 1) and the scenario that incorporated the overhead sign (Configuration 2), considering the four zones of interest. The results show significant differences in mean speeds for Zone 3 at a 95% confidence level for Scenarios 1 and 2 and a 90% confidence level for Scenario 4. Thus, the overhead sign appears to have a positive effect by generating a significant reduction in mean speeds when a pedestrian crosses the street, either from the right or from the left, during daytime and nighttime.

The results presented in Table 5.5 indicate no significant differences in mean speeds between Configurations 1 and 2 in Zones 1, 2, and 4. Only Scenario 5 in Zone 2 presents a significant difference at a 90% confidence level. Therefore, drivers present similar behavior in terms of mean speed in those zones where there is no pedestrian presence.

Table 5.5 - Comparison of mean speeds and standard deviation of speeds

Scenario	Zone	Mean Speed (mph)		Standard Deviation of Speed (mph)	
		Configuration 1	Configuration 2	Configuration 1	Configuration 2
1	1	42.51	42.33	0.23	0.22
1	2	46.56	44.82	0.13	0.19
1	3	40.41*	32.86*	4.91	6.63
1	4	40.56	36.59	0.24	0.29
2	1	43.12	42.29	0.20	0.19
2	2	47.05	43.08	0.16*	0.07*
2	3	39.12*	28.71*	5.02	7.21
2	4	43.44	37.85	0.19	0.24
3	1	41.68	41.94	0.28*	0.15*
3	2	43.96	42.43	0.11	0.09
3	3	43.57	41.53	0.31	0.38
3	4	42.55	40.47	0.07	0.06
4	1	41.62	40.78	0.23	0.18
4	2	47.22	42.42	0.15	0.12
4	3	41.07**	29.67**	3.00	5.02
4	4	46.25	38.23	0.19	0.18
5	1	40.25	40.56	0.25	0.23
5	2	47.48**	40.69**	0.11	0.16

5	**3**	33.72	26.30	5.96	6.35
5	**4**	39.97	36.87	0.32	0.27
6	**1**	40.43	39.56	0.21	0.19
6	**2**	44.21	40.96	0.14	1.27
6	**3**	44.33	40.24	0.33	0.68
6	**4**	44.66	40.27	0.05	0.08

5.2.3 Reaction to Crossing Pedestrian

A trajectory analysis of vehicle and pedestrian positions and speeds along the twelve scenarios was performed. Figure 5.7 shows the position and speed data for a particular subject in Scenario 1 of Configuration 1. The coordinates of the X-axis run from right to left. For example, the line that represents the changes in vehicle position with time starts at the far right and moves towards the left. The Y-axis has two sets of scales. The left scale represents the lateral roadway position of the pedestrian and the vehicle (m), and the right scale refers to the vehicle speed (mph). The line representing the speed data points (blue line) is obtained by plotting the speed data every 0.02 seconds. There are two sets of data points related to the lateral position, one for the vehicle (circles) and another for the crossing pedestrian (triangles). Each color corresponds to a respective position at a particular moment of the simulation, every second, for the pedestrian crossing the road and for the vehicle approaching the pedestrian trajectory. For Scenario 1, the pedestrian trajectory was from the shoulder to the median (represented as the triangles going down in the graph). Therefore, Point 1 in the vehicle trajectory corresponds to the position of the vehicle at the same instant that the pedestrian started walking from the side-street sidewalk towards the PR-2 arterial, and Point 10 corresponds to the instant when the pedestrian cleared the pavement and arrived at the raised median.

Points 5 and 7 in Figure 5.7 are of particular interest to determine the potential conflict with the pedestrian. Point 5 corresponds to the instant when the pedestrian crossed the white lane marking on the right edge. Figure 5.8a shows this condition as it was presented in the driving simulator scenario. Point 7 corresponds to the instant when the pedestrian was in the middle of the highway. Figure 5.8b shows this condition as presented in the driving simulator scenario. The position of the pedestrian is circled in both figures. Since each driver negotiated the scenario in a different manner, a specific analysis was performed for each subject. Figure 5.7 shows that this particular subject reduced speed when the pedestrian was crossing Point 6 (entering the traveled way). Also, the driver rapidly moved from the center lane to the right lane, as indicated by the lateral displacement observed between Points 8 and 9 of the vehicle trajectory. By reducing the speed and changing to the right lane, the subject driver avoided collision with the pedestrian in this case. See Appendix E for graphical representations of vehicle speed and position for all experimental scenarios.

When analyzing the data for the position and speed of all subjects for all scenarios while the pedestrian was crossing the street, it was noted that the primary reactions to the presence of the crossing pedestrian were changes in speed. Lane-changing maneuvers were observed for only two of the 96 cases. Therefore, the subsequent analysis focus on vehicle speeds.

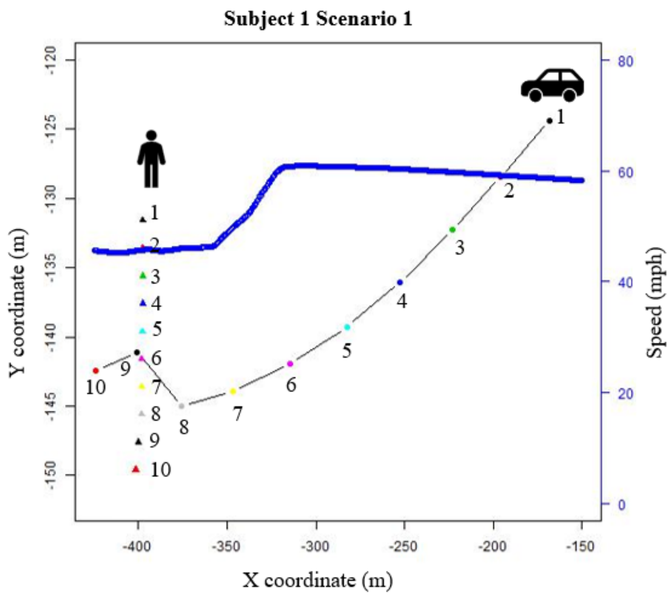

Figure 5.7 - Position and speed profiles of a particular subject

(a) Pedestrian crossing the white right lane line (b) Pedestrian in the middle of the highway

Figure 5.8 - Positions of the pedestrian in the driving lanes

The analysis of the driver's reaction to the presence of a pedestrian crossing the street centered on Zone 3. Three types of analysis were performed. First, the position and speed during the time that the pedestrian crossed the street were depicted, as shown in Figure 5.7, for each of the subjects to determine their reactions (changes in speed and lane changes). Second, the data related to changes in speed was summarized in Table 5.6, which shows the speed reduction for each scenario. Third, the specific speed reduction in Zone 3 (maximum speed – minimum speed) was calculated for each subject in each scenario. The average of the individual speed differences was calculated for each scenario and compared for Configurations 1 and 2.

Table 5.7 shows the difference between the mean speeds for Configuration 2 and Configuration 1.

Table 5.6 - Speed reductions in Zone 3

Configuration	Scenario	Number of Subjects that Reduced Speed			
		0 – 5 mph	6 – 15 mph	16 – 25 mph	>25 mph
1	1	5	3	1	3
	2	4	5	0	3
	3	12	0	0	0
	4	5	5	1	1
	5	2	4	3	3
	6	12	0	0	0
2	1	2	4	3	3
	2	4	1	1	6
	3	12	0	0	0
	4	3	4	0	5
	5	2	5	1	4
	6	11	1	0	0

According to the results in Table 5.7, the presence of the overhead sign (Configuration 2) generated a greater reduction in mean speed. The reduction was particularly higher for Scenarios 1, 2, and 4, due to the presence of the pedestrian in the simulation. Consolidating this analysis for Zone 3 with the previous analysis for Zones 1, 2, and 4, drivers showed similar speeds before the influence of the overhead sign for Configurations 1 and 2, but had a higher reaction (greater speed reductions) with the presence of the overhead sign.

Table 5.7 - Mean speed differential in Zone 3

Scenario	Mean Speed Difference (mph)

	Configuration 2	**Configuration 1**	**Configuration 2 – Configuration 1**
1	17.96	12.44	5.53
2	21.81	13.51	8.29
3	1.27	0.97	0.30
4	17.08	9.38	7.71
5	19.56	19.02	0.54
6	2.36	1.14	1.22

6 Conclusions

This study evaluated the effect of TCDs on driver performance in and around two school zones using a driving simulator. The variables obtained from the simulator were mean speed, acceleration noise, and lateral position. Scenarios were evaluated considering changes in signage configuration, presence of pedestrians, time of day, vehicles parked on the shoulder, and traffic. A total of 60 subjects participated in the experiments, 36 in the study of the S.U. Samuel Adams School and 24 in the study of the Franklin D. Roosevelt School. The major conclusions associated with each school zone are presented below.

6.1 S.U. Samuel Adams

The online survey demonstrated that close to half of the drivers lacked an understanding of the fundamental meaning of the School Zone (51%) and School Crosswalk signs (47%). This lack of understanding of school zone signs presents a significant safety issue in school zones, especially when speeding and distracted users are involved. *Elementary students* are more vulnerable and failed to adequately recognize the risk when crossing the road or walking along the school zone. *Middle or high school students* are typically prone to take more risks on the road, which can result in serious injuries and fatalities.

The combination of an overhead speed sign with alternate flashing beacons and pavement markings has the potential to reduce speed across school zones. Reduced speed behavior should lower the severity of crashes. The proposed combination of TCDs provide drivers clear and more visible information, give adequate time for a proper response, and provide effective guidance for drivers entering a school zone, among other benefits.

The results of the simulation experiment showed a reduction in *mean speed* in the proposed TCD configuration for 70.8% of the zones evaluated in the scenarios. As expected, the configuration with the new combination of TCDs was effective in promoting a reduction in *mean speed* in all four zones of the school zone when compared with the existing TCD configuration.

The mean position variable was not affected by the proposed TCDs. The stimuli associated with the presence of a pedestrian in the shoulder appeared to affect the lane-selection decision of the drivers. The P-value of the T-test for the *mean position* variable was statistically significant in three zones in Scenario 4. In Scenario 4 of Configuration 2, subject drivers tended to change to the left lane earlier. In this scenario, the driver had longer visibility of the pedestrian because there were no vehicles parked in the shoulder and no traffic. In Scenario 12, subjects in Configuration 1 stayed in the right lane most of the time, as opposed to Configuration 2, wjere the subjects split between lanes.

The presence of the proposed TCD was effective in reducing the change in acceleration in Zone 2 for 25% of the scenarios. Zone 2 is where subject drivers were expected to reduce their speed from 45 mph to 25 mph since they were about to enter the school zone. This reduction in acceleration noise is positive because it is associated with a reduction in the possibility of crashes.

6.2 Franklin D. Roosevelt

The results of the survey indicated that a sign on an overhead support with flashing beacons effectively conveyed the presence of pedestrians on the roadway. For this reason, the advanced warning overhead sign with flashing beacons was used as the proposed configuration.

In the four scenarios where a pedestrian was crossing the road, the proposed TCD was effective in reducing the mean speed in Zone 3. In 75% of these scenarios, the difference was statistically significant. Zone 3 is where the pedestrian starts to encroach the road. The general pattern observed was that the value of the mean speed was lower for Configuration 2, except at Zone 1 (before the warning sign was readable) for Scenarios 3 (daytime with no crossing pedestrian) and 5 (nighttime with crossing pedestrian). The advanced warning sign did not require drivers to lower their speeds on the roadway section; it just warned of the potential presence of pedestrians.

In terms of validating the second hypothesis about the reaction of drivers in free-flow conditions to the presence of the crossing pedestrian, there was evidence of speed reduction when the configurations were compared. Drivers primarily adjusted their behavior by reducing speed rather than performing an evasive maneuver (i.e., changing lanes). Drivers performed a lane-change maneuver in only two of the 96 cases with a potential conflict created by a crossing pedestrian. The presence of the overhead warning sign in Configuration 2 did result in greater speed reductions in Zone 3, particularly for Scenarios 1, 2, and 4. Therefore, the overhead warning sign may help drivers be more observant and alert to the presence of pedestrians in the roadway environment, causing them to react effectively to avoid a potential collision with a pedestrian.

7 Recommendations and Future Research

The recommendations for school zones on suburban high-speed arterials presented here are based on the results of this driving simulation study with an emphasis on TCDs. Recommendations for future research based on these findings are also presented.

7.1 S.U. Samuel Adams

The proposed TCDs showed potential for reducing speeds in school zones. Therefore, their implementation should be evaluated in terms of crash-reduction potential and cost effectiveness. The effectiveness of other types of TCDs, such as interactive vehicle speed display signs and in-vehicle driver assistant messages, should be studied with a driving simulator. Based on the 20 mph reduction in speed limit at the S.U. Samuel Adams School, additional strategies such as two-step speed reduction signs should be evaluated using driving simulation to validate the positive effects that have been observed in micro-simulation studies.

For future research related to the S.U. Samuel Adams school zone, an analysis of the segments directly related to the beginning and end of the school zone is needed to evaluate how drivers decelerate and accelerate, respectively. Furthermore, the simulation study should evaluate the impact that educational training and enforcement has on the effectiveness of the proposed TCD combination.

7.2 Franklin D. Roosevelt

The principal recommendation associated with the research at Franklin D. Roosevelt is to implement the proposed advanced overhead warning sign with flashing beacons to effectively alert drivers of the midblock pedestrian crossing.

Future studies in the Franklin D. Roosevelt school zone could include the following:

- Evaluate the effect of including regulatory or warning signs related to lower speeds, in addition to the pedestrian presence warning sign.
- Assess the effect of ambient traffic to detect unsafe deceleration rates applied by drivers when approaching the crossing pedestrian, which could result in rear-end crashes.
- Develop advanced active warning messages using vehicle-to-infrastructure communication to alert drivers to the presence of pedestrians and the potential conflicts from these mid-block crossing maneuvers.
- Future driving simulation studies could evaluate the effectiveness of the redundancy of several advanced warning signs on the roadway or the repetition of active warning messages in smart infrastructure.

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APPENDICES

Description of Appendices

This research effort consisted of an online survey, the evaluation of two school zones (S.U. Samuel Adams and Franklin D. Roosevelt) adjacent to high speed major arterials of the National Highway System, and a comprehensive analysis of different scenarios and variables applicable to these school zones using the UPRM driving simulator.

The six appendices includes the school zone survey questionnaire (Appendix A), the graphical analysis of speeds, position, and acceleration noise of S.U. Samuel Adams school (Appendices B, C, and D), and pedestrian time to collision and speeds of Franklin D. Roosevelt school zone (Appendices E and F).

Appendix A: School Zone Survey Questionnaire

School Zone Survey

* Required

School Zone Survey Agreement

This survey aims to understand what is the perception of drivers in school zones or the vicinity of a school.

Requirements:
- Older than 18 years-old
- At least 18 months of driving experience
- Current driver's license in any of the States or Territories of the United States.
- Usually drive in any of the States or Territories of the United States.

Your participation will consist in answering an electronic questionnaire in which demographic information of the participants will be obtained. It will be asking about road signage and pavement markings that are near a school zone. The survey lasts approximately 20 minutes.

Your participation is voluntary. Which indicates that you will not be prejudiced to complete the survey.

If you meet all the requirements and wish to participate, please proceed to the questions.

Do you accept to participate in this study voluntarily? *

- ○ Yes
- ○ No

School Zone Survey

* Required

Demographics

1.Do you have a valid driver license?

- ◯ Yes
- ◯ No

2.State or territory where you usually drive:

Choose ▾

3. Age

Choose ▾

4.Indicate your gender

- ◯ Female
- ◯ Male
- ◯ Other:

5.Indicate your ethnicity

- ◯ White
- ◯ Hispanic or Latino
- ◯ Black or African American
- ◯ Native American or American Indian
- ◯ Asian / Pacific Islander
- ◯ Other:

6.Indicate the highest education level achieved

- ○ Some high school, no diploma
- ○ High school graduate, diploma or the equivalent (for example: GED)
- ○ Associate degree
- ○ Bachelor's degree
- ○ Master's degree
- ○ Doctorate degree
- ○ Other:

7.Do you travel thru a school zone in your daily trips?

- ○ Yes
- ○ No

8.How many school age kids do you take to school? *

- ○ 0
- ○ 1
- ○ 2
- ○ 3+

School Zone Survey

School Transportation

8.Indicate the type of school the kids currently go to.
Select all that apply

	Public School	Private School	Homeschooling	Other
Elementary School	☐	☐	☐	☐
Middle School	☐	☐	☐	☐
High School	☐	☐	☐	☐

9. Does the school has a pick-up & drop-off zone?

If your kids go to different schools please indicate your answer in the option " Other" . A pick-up & drop-off zone is an area designated on the side of the road to legally leave or pick up students at the school.

- ○ Yes
- ○ No
- ○ I don't know/Not sure
- ○ Other:

10.Select the travel method(s) the kids typically use to or from school

Select all that apply

	Walk	Cycling	Private Car	School-Bus	Other
Pre-School	☐	☐	☐	☐	☐
Elementary School	☐	☐	☐	☐	☐
Middle School	☐	☐	☐	☐	☐
High School	☐	☐	☐	☐	☐

11.Have you been involved in a crash while traveling to or from school?

- ○ Yes
- ○ No

School Zone Survey

School Zone

12.Do you think that applying a reduced speed limit in the proximity of a school would be an effective road safety measure?

	Yes	No	Not sure
Elementary School	○	○	○
Middle School	○	○	○
High School	○	○	○
K-12	○	○	○

13.Assume that school activities were limited to occur from 8 AM to 3 PM, how appropriate you think will be to apply a reduced speed limit on the school zone during the following time periods?

	Absolutely appropriate	Slightly appropriate	Neutral	Slightly inappropriate	Absolutely inappropriate
At all times	○	○	○	○	○
From 6 AM to 7 PM	○	○	○	○	○
From 6 to 8 AM and from 3 to 5 PM	○	○	○	○	○
From 7 to 9 AM and from 2 to 4 PM	○	○	○	○	○
Only when students are present at the roadside	○	○	○	○	○
Only when flashing beacons are active	○	○	○	○	○

14.At what speed do you usually drive on a school zone?

	10mph	15mph	20mph	25mph	30mph	Higher than 30 mph
In an urban area	○	○	○	○	○	○
In a rural area	○	○	○	○	○	○

15.What is the statutory speed limit in a school zone in your jurisdiction?

	10mph	15mph	20mph	25mph	30mph	Higher than 30 mph	Don't Know
In an urban area	○	○	○	○	○	○	○
In a rural area	○	○	○	○	○	○	○

16.Which is the safe speed limit you recommend for a school zone?

	10mph	15mph	20mph	25mph	30mph	Higher than 30 mph
In an urban area	○	○	○	○	○	○
In a rural area	○	○	○	○	○	○

School Zone Survey

Signs

17. What do you understand by this sign?

- ○ Pedestrian Crosswalk
- ○ School Zone
- ○ Family Crosswalk
- ○ School Crosswalk
- ○ Other:

18. What do you understand by this sign?

- ○ Pedestrian Crosswalk
- ○ School Zone
- ○ Family Crosswalk
- ○ School Crosswalk
- ○ Other:

19. What do you understand by this sign?

- ○ Pedestrian Crosswalk
- ○ School Zone
- ○ Family Crosswalk
- ○ School Crosswalk
- ○ Other:

20. Which pavement marking option delimits best the school zone?

A)

B)

- ○ A
- ○ B
- ○ Other:

School Zone Survey

Alternative Signs Part 1:

Questions 21A to 21D present alternative signage for school zones. How effective you think are the following signs in informing drivers of the posted speed limit on a school zone?

21A.Overhead Signage with Flashing Beacons:

- Extremely effective
- Slightly effective
- Neutral
- Slightly ineffective
- Extremely ineffective

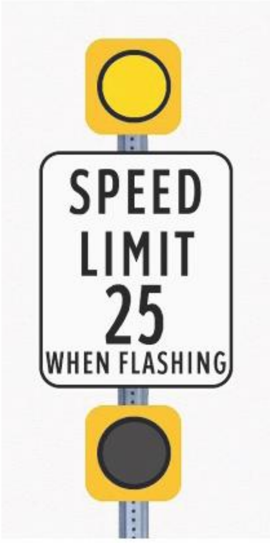
21B.Roadside signage with supplementary plaque:

- Extremely effective
- Slightly effective
- Neutral
- Slightly ineffective
- Extremely ineffective

21C.Roadside signage

- Extremely effective
- Slightly effective
- Neutral
- Slightly ineffective
- Extremely ineffective

21D.Roadside Signage with Flashing Beacons



- Extremely effective
- Slightly effective
- Neutral
- Slightly ineffective
- Extremely ineffective

School Zone Survey

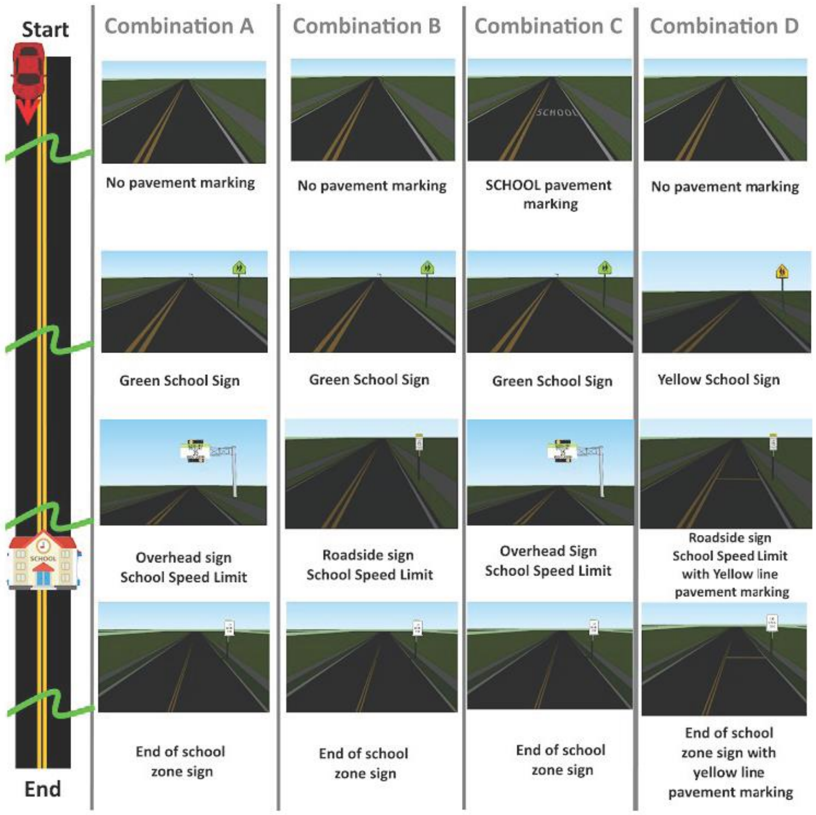
Alternative Signs Part 2:

In the proximity of a school, which one of the following four combinations of signs and pavement markings you think is the best to help drivers comply with the speed limit?

*See all the combination and enumerate them in ascending order using 1 for the best combination and 4 for the worst combination.

22.Signage and Marking Combinations

The letter at the top left corner identifies the combination. You will see four images for each of the four combinations(A,B,C,D).



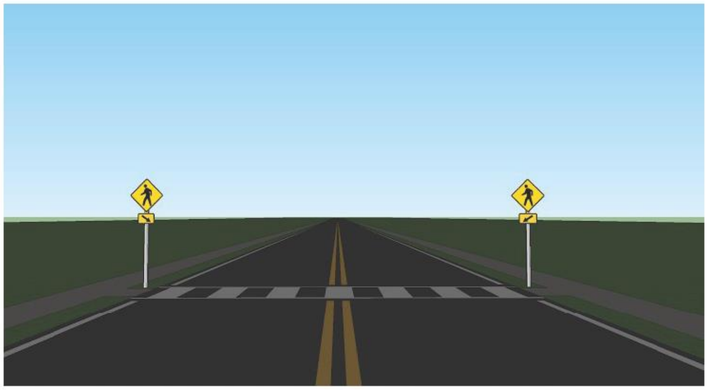
	Combination A	Combination B	Combination C	Combination D
1 Very desirable	○	○	○	○
2 Desirable	○	○	○	○
3 Neutral	○	○	○	○
4 Undesirable	○	○	○	○

School Zone Survey

Pedestrian Crosswalks

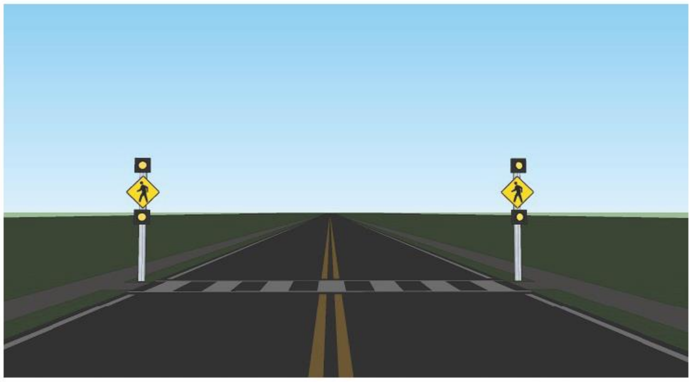
Questions 23A to 23D present alternative signage for pedestrian crosswalks. How effective you think are the following signs in informing drivers to identify the presence of a crosswalk?

23A. Roadside Signage



- Extremely effective
- Slightly effective
- Neutral
- Slightly ineffective
- Extremely ineffective

23B. Roadside Signage with Flashing Beacons

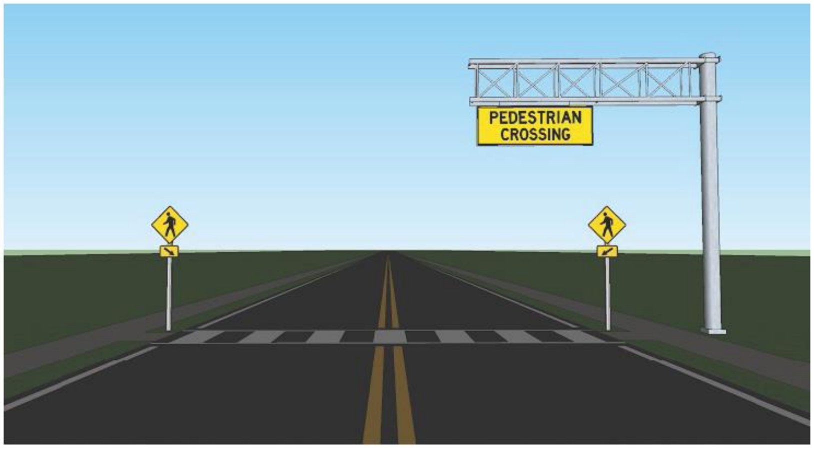


- Extremely effective
- Slightly effective
- Neutral
- Slightly ineffective
- Extremely ineffective

23C.Overhead Signage

- ○ Extremely effective
- ○ Slightly effective
- ○ Neutral
- ○ Slightly ineffective
- ○ Extremely ineffective

23D.Overhead and Roadside Signage



- ○ Extremely effective
- ○ Slightly effective
- ○ Neutral
- ○ Slightly ineffective
- ○ Extremely ineffective

Appendix B: S.U. Samuel Adams Speeds

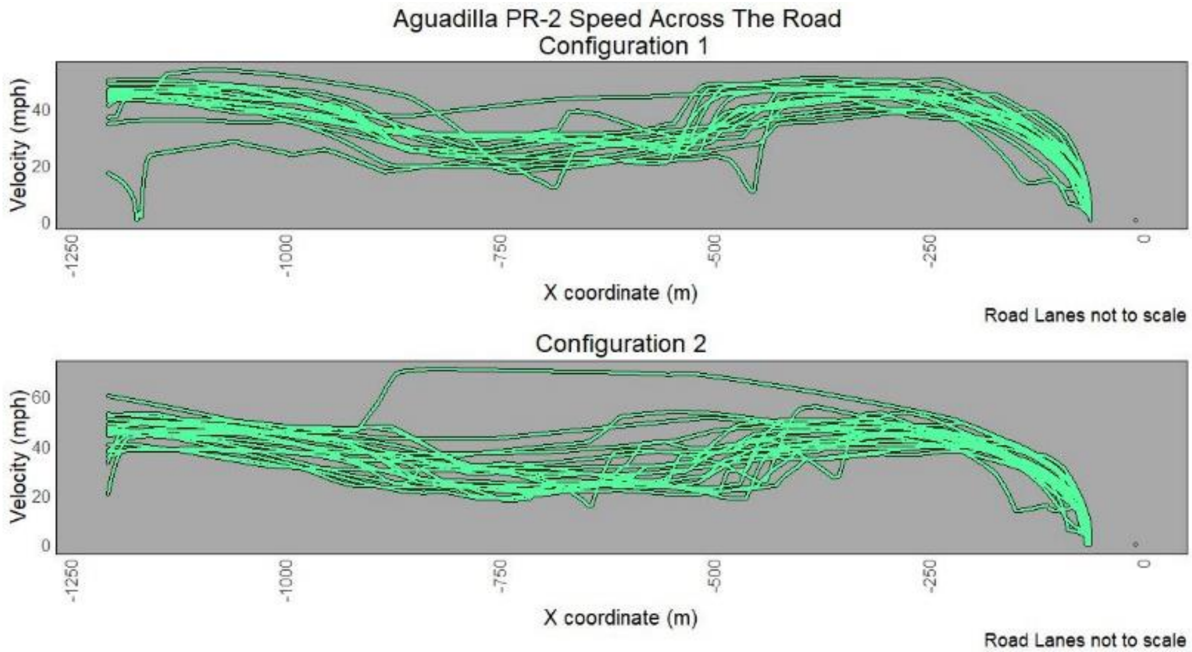


Figure B. 1 - Scenario 1 subjects' speed by configuration

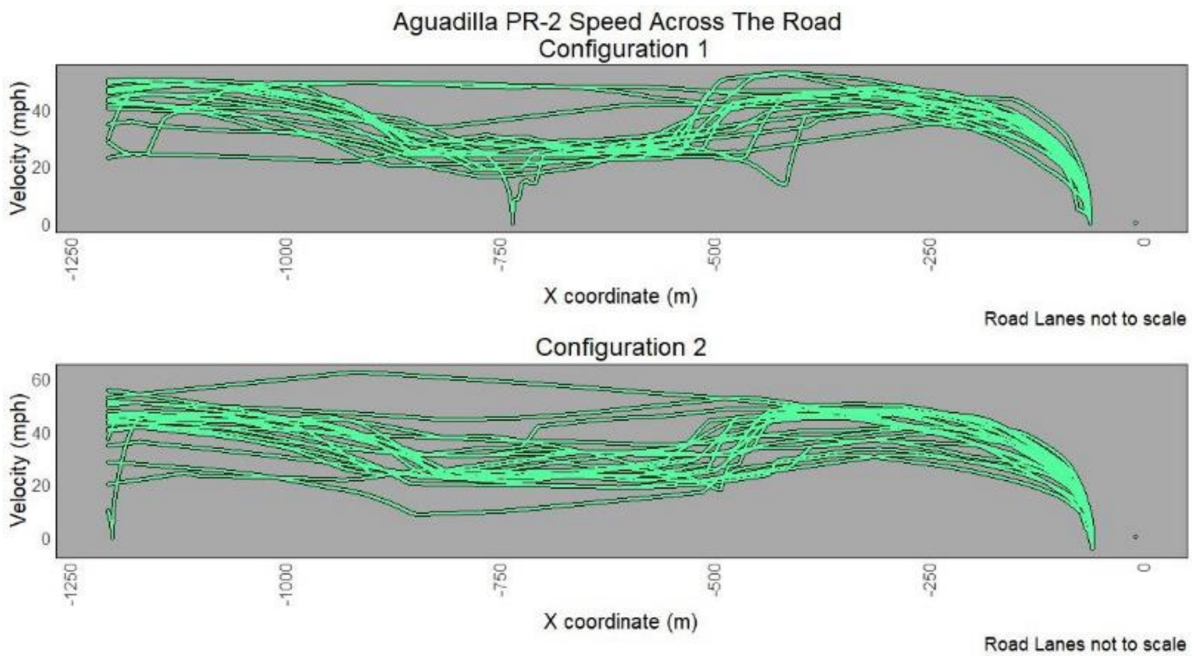


Figure B. 2 - Scenario 2 subjects' speed by configuration

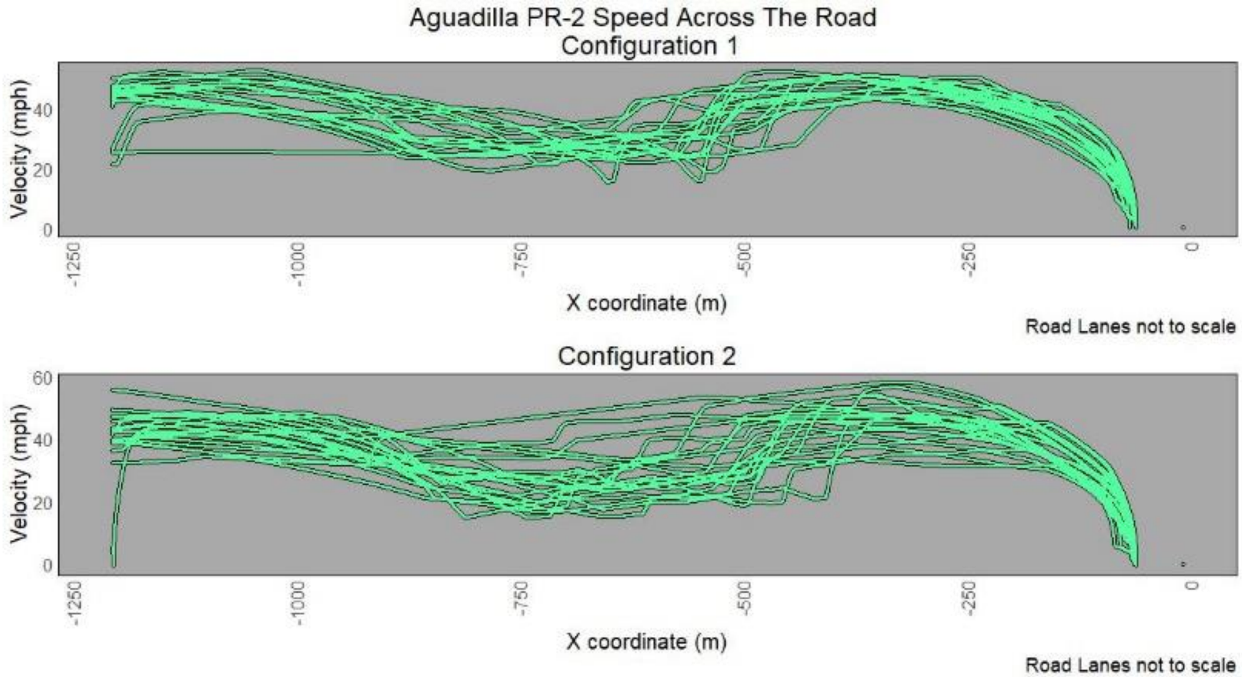


Figure B. 3 - Scenario 3 subjects' speed by configuration

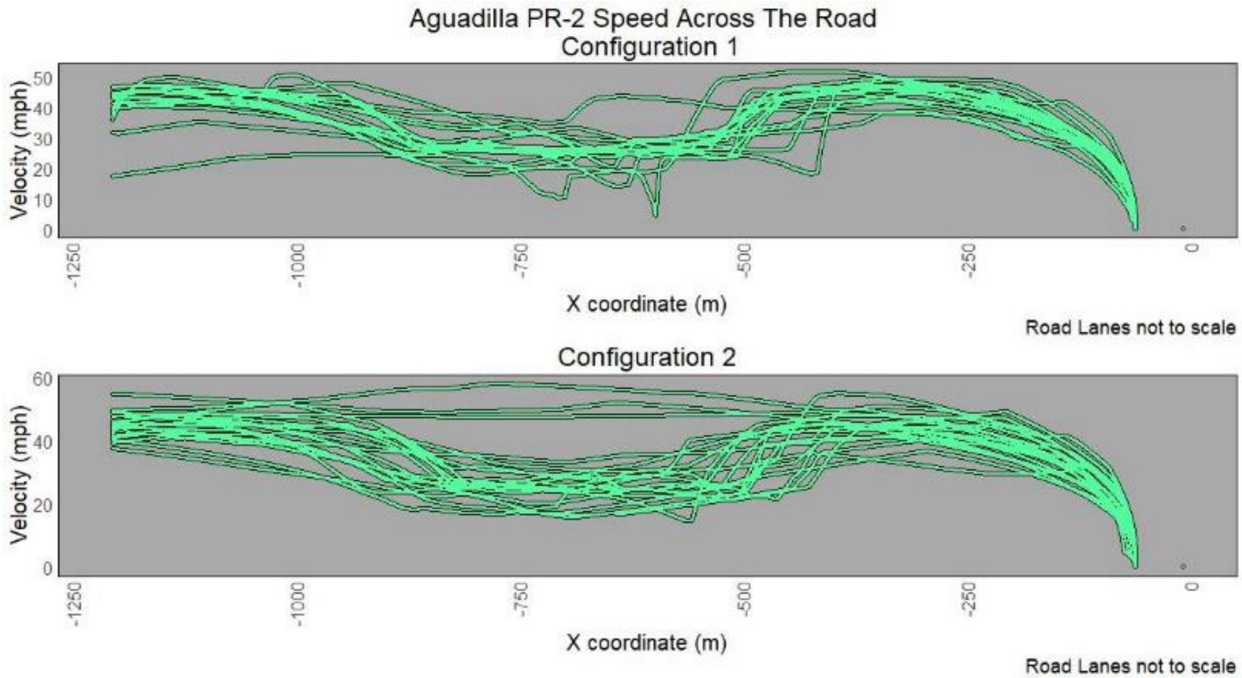


Figure B. 4 - Scenario 4 subjects' speed by configuration

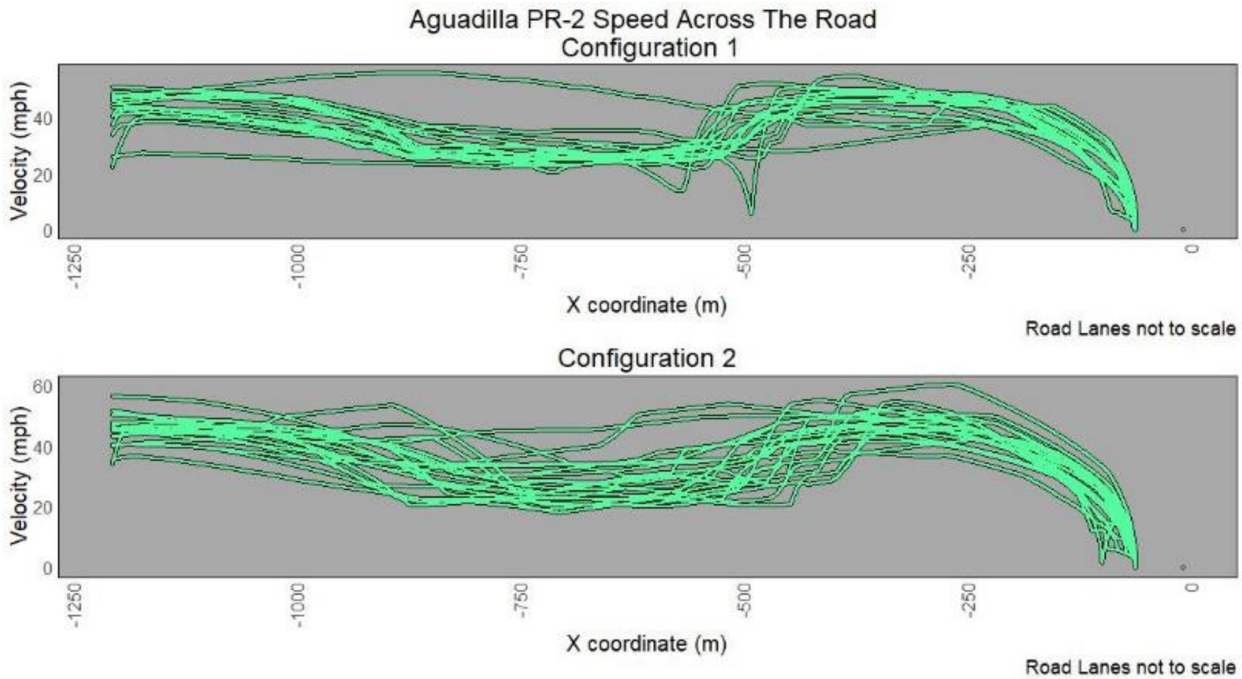


Figure B. 5 - Scenario 5 subjects' speed by configuration

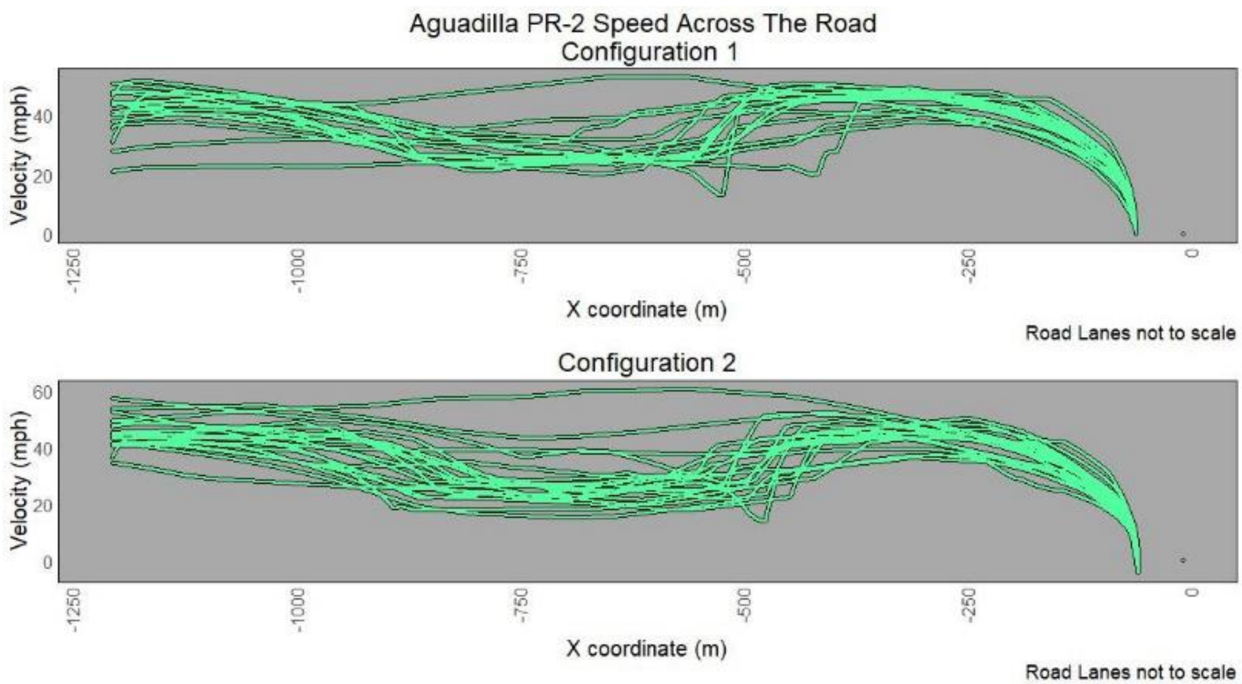


Figure B. 6 - Scenario 6 subjects' speed by configuration

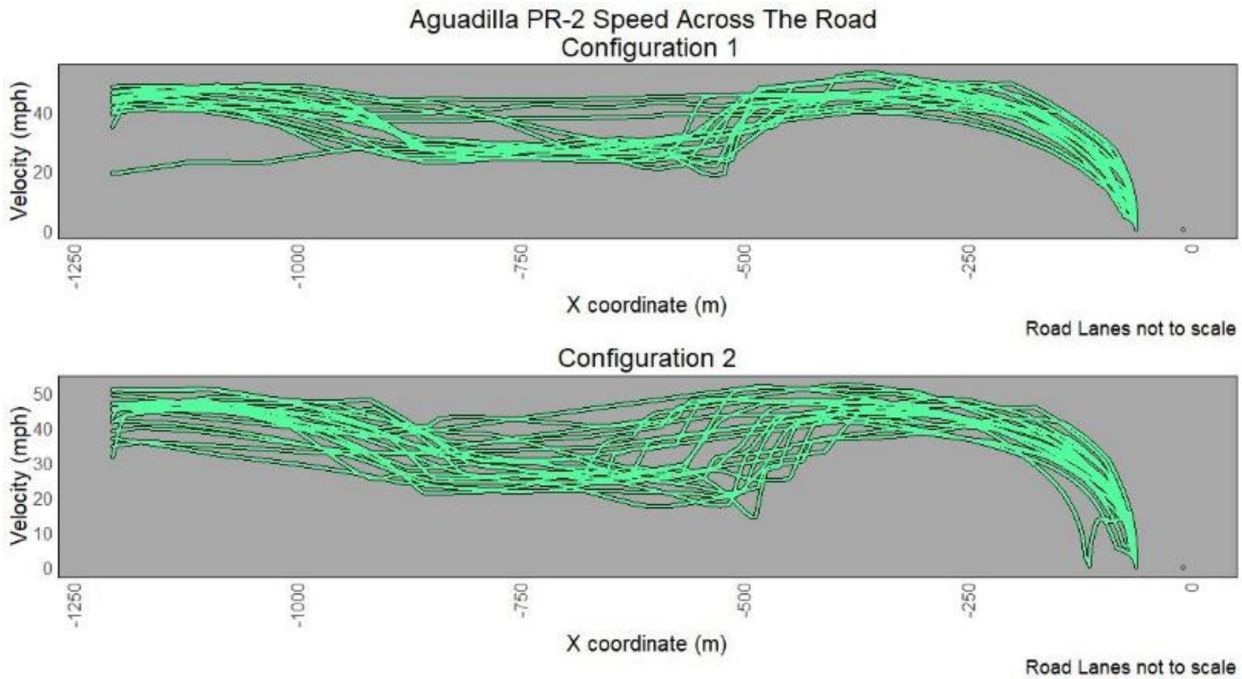


Figure B. 7 - Scenario 7 subjects' speed by configuration

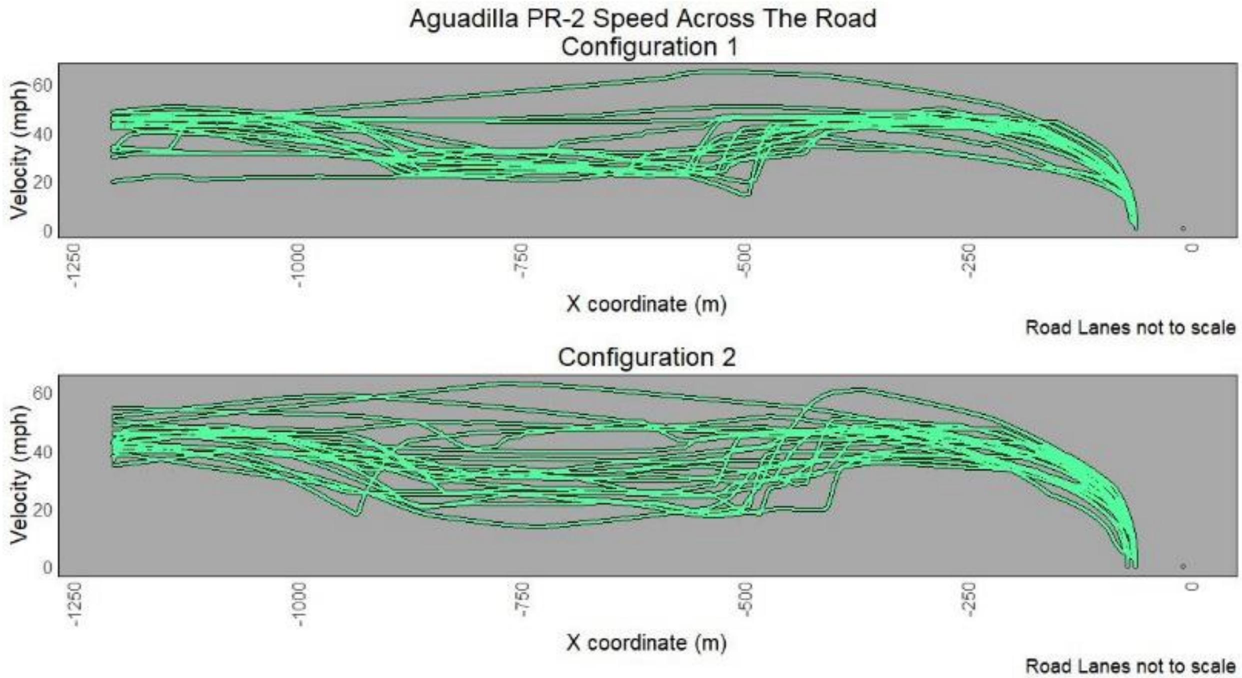


Figure B. 8 - Scenario 8 subjects' speed by configuration

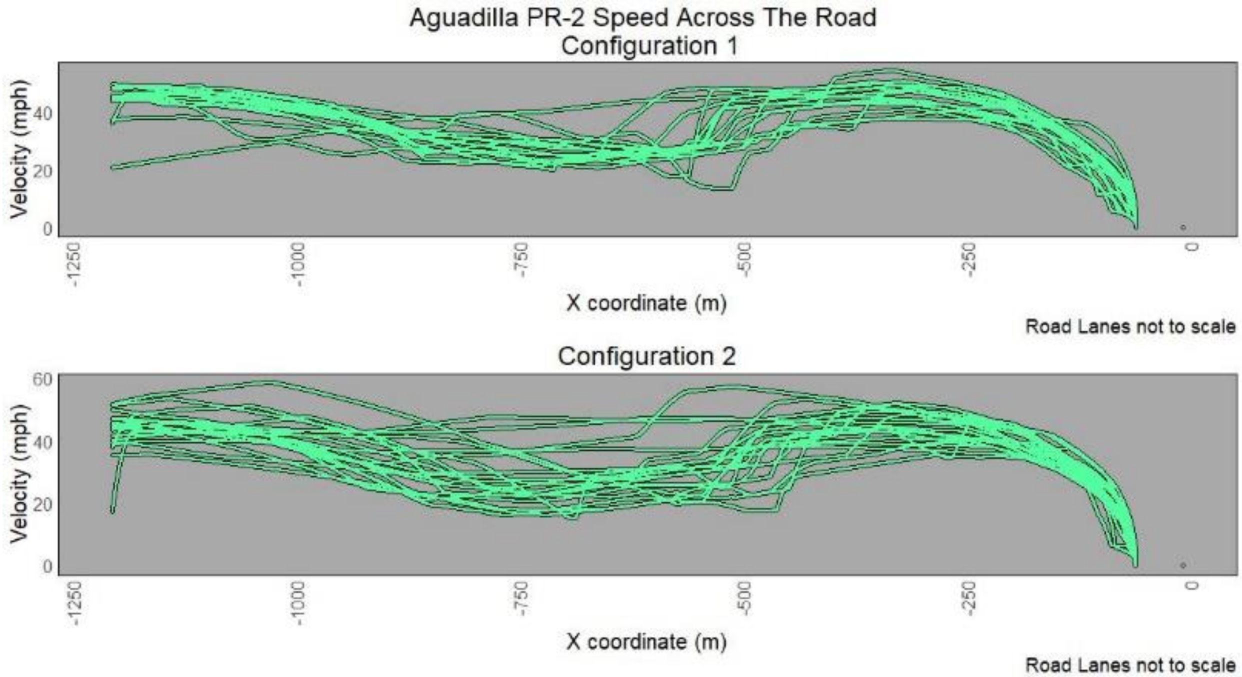


Figure B. 9 - Scenario 9 subjects' speed by configuration

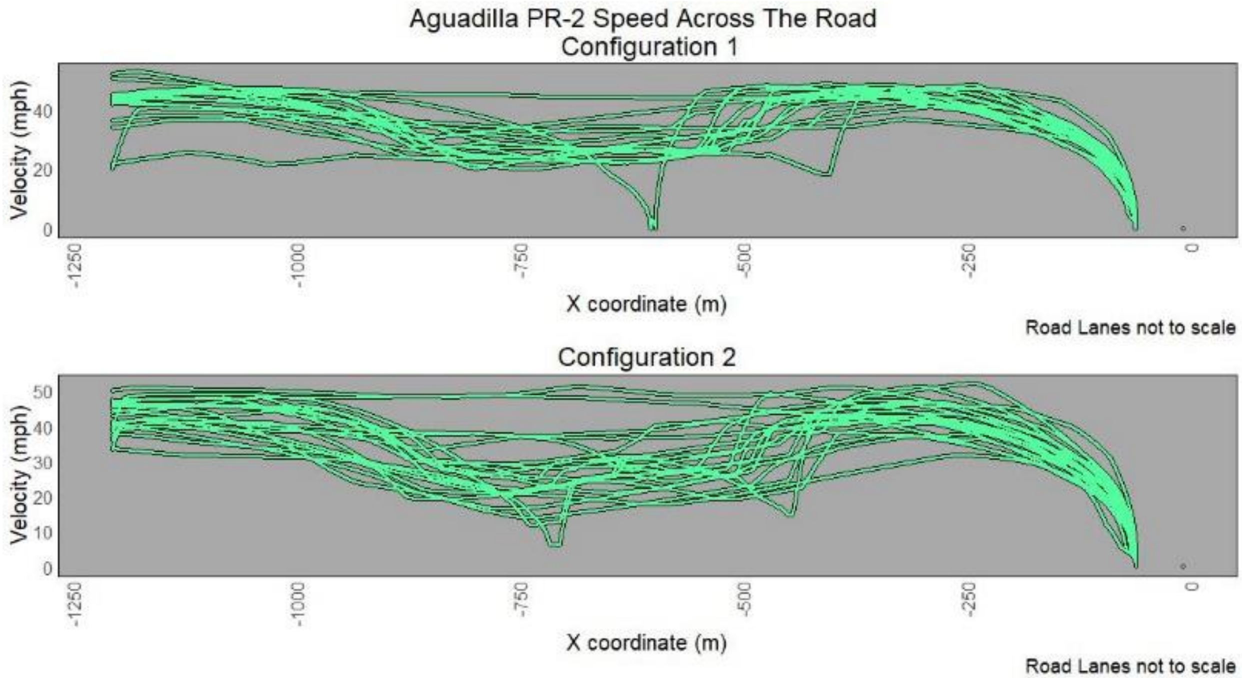


Figure B. 10 - Scenario 10 subjects' speed by configuration

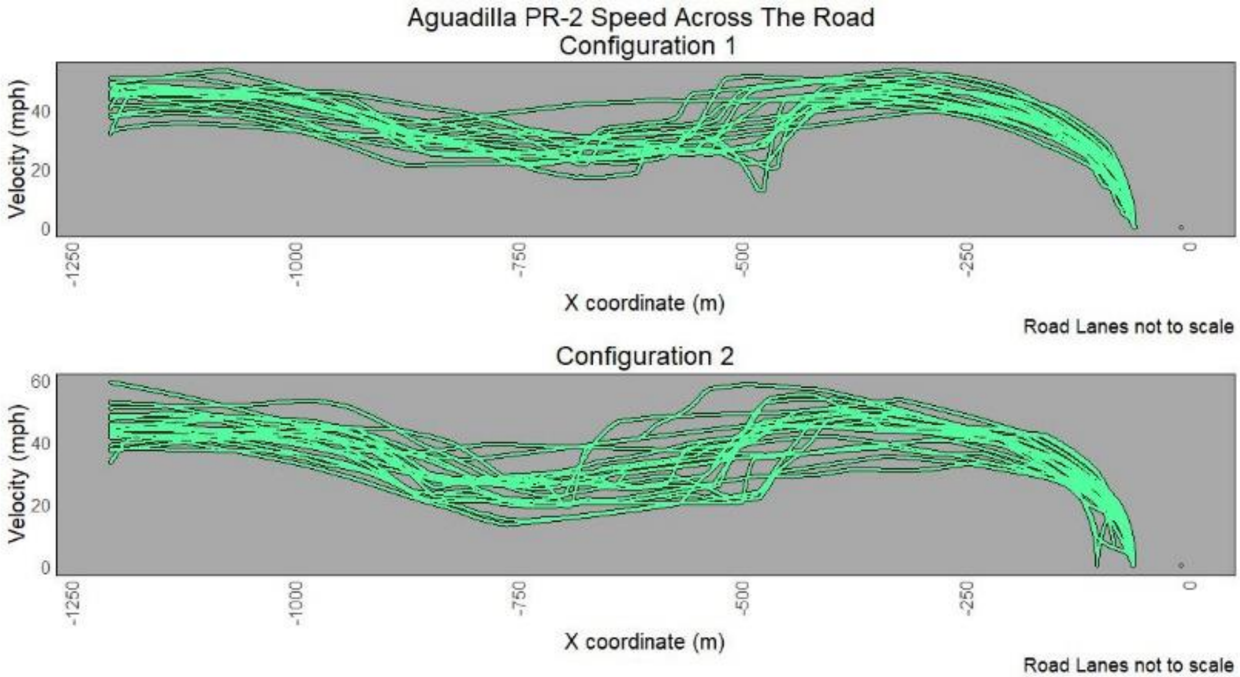


Figure B. 11 - Scenario 11 subjects' speed by configuration

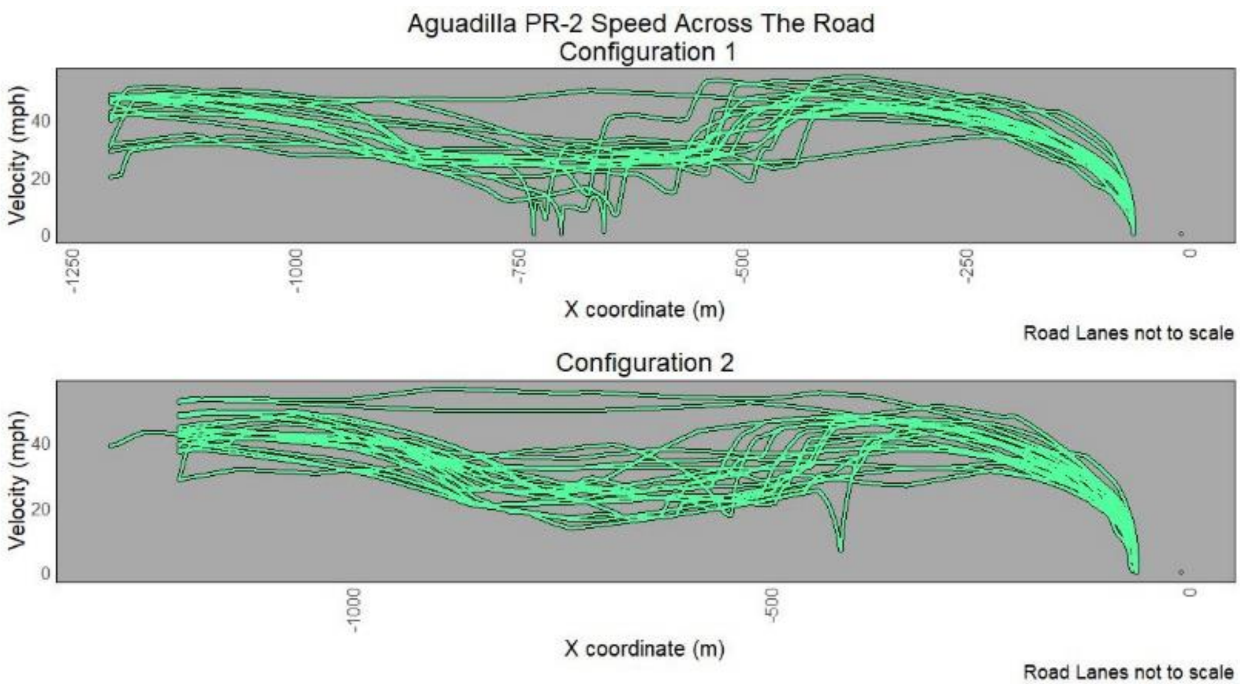


Figure B. 12 - Scenario 12 subjects' speed by configuration

Appendix C: S.U. Samuel Adams Position

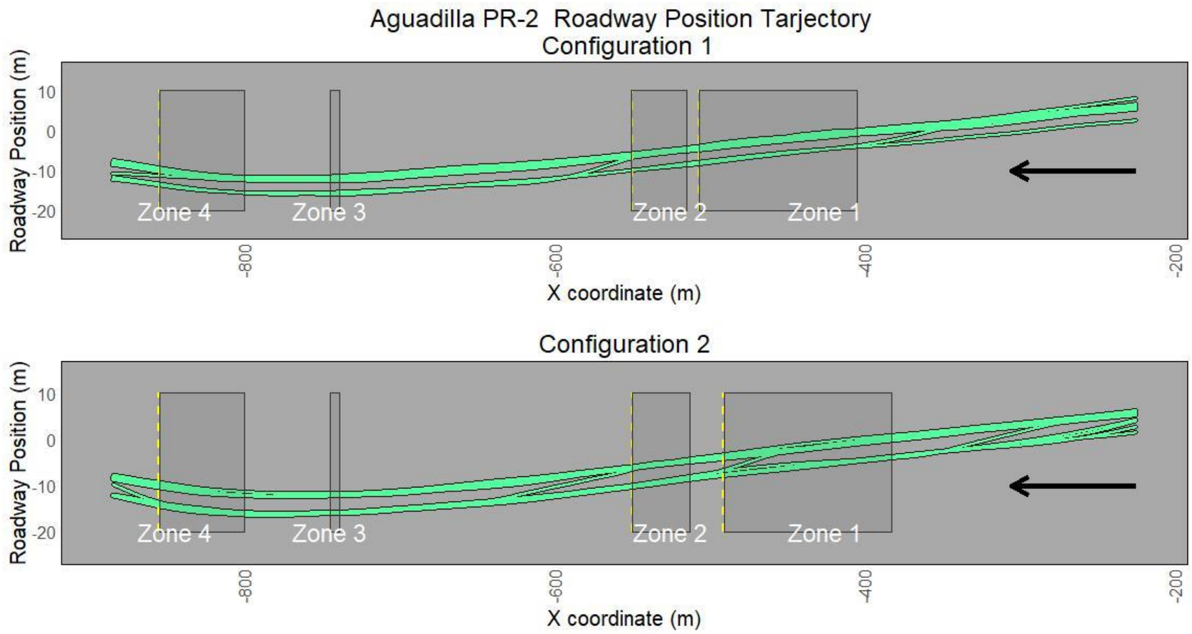


Figure C. 1 - Scenario 1 subjects' position by configuration

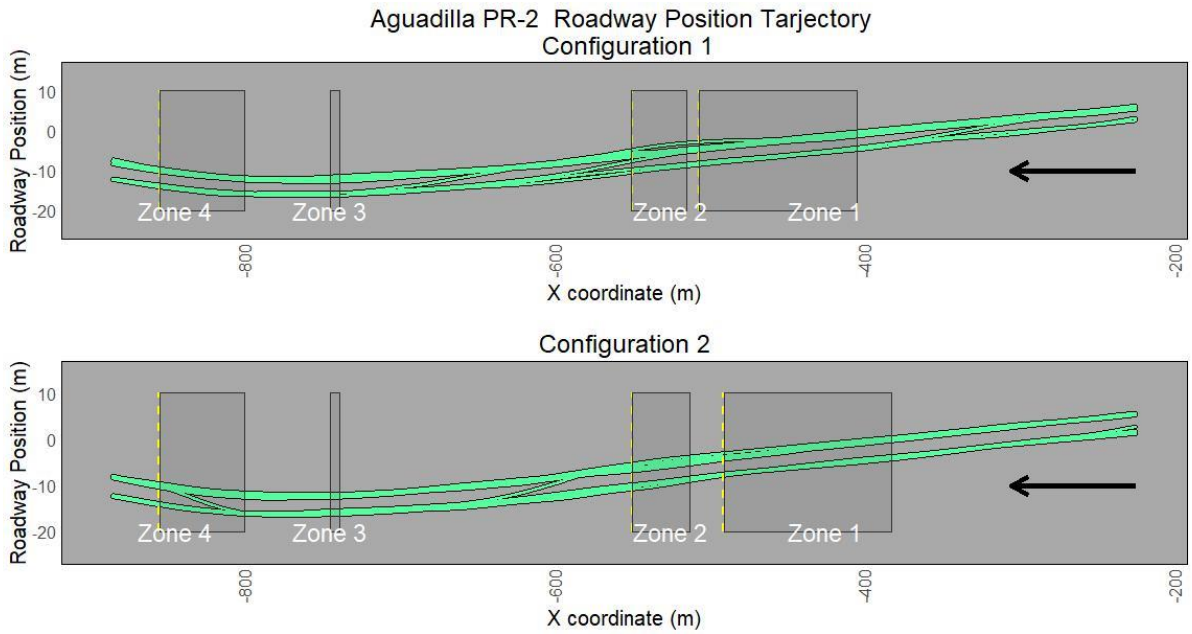


Figure C. 2 - Scenario 2 subjects' position by configuration

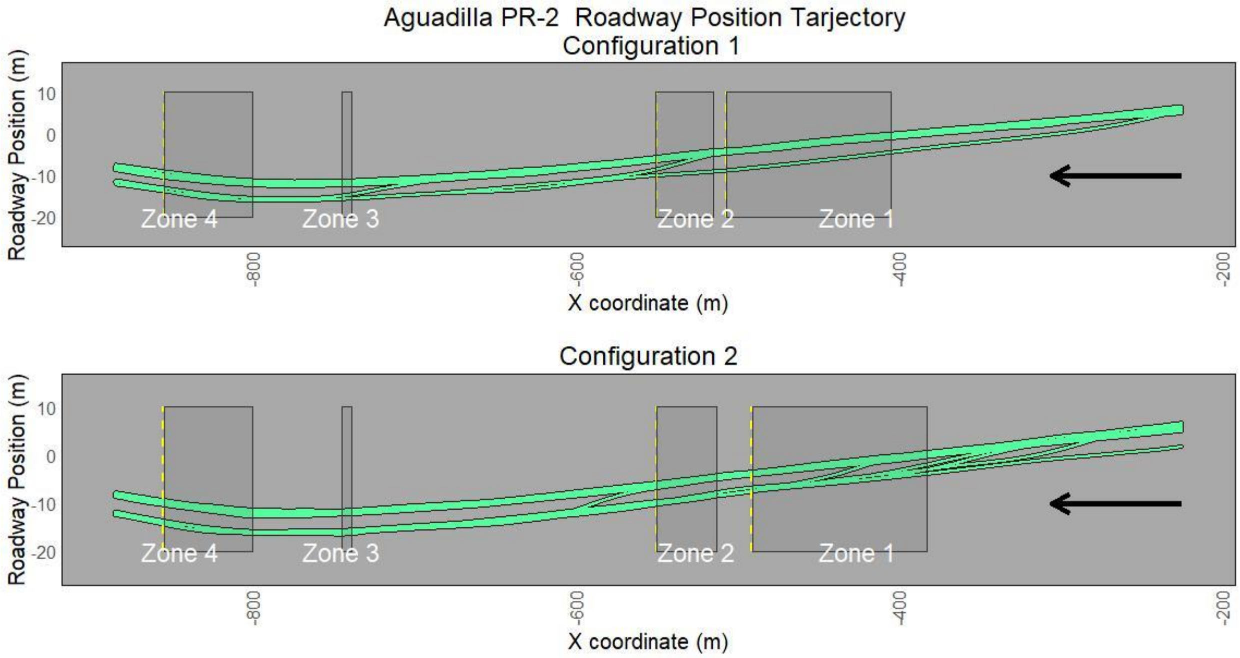


Figure C. 3 - Scenario 3 subjects' position by configuration

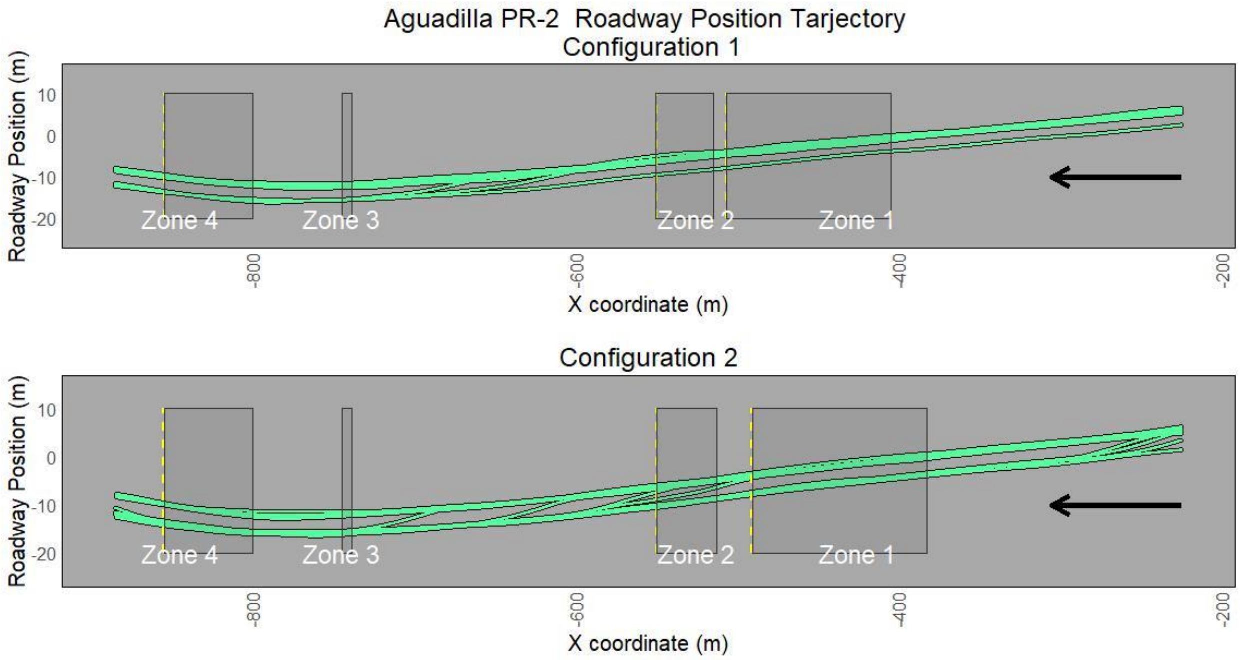


Figure C. 4 - Scenario 4 subjects' position by configuration

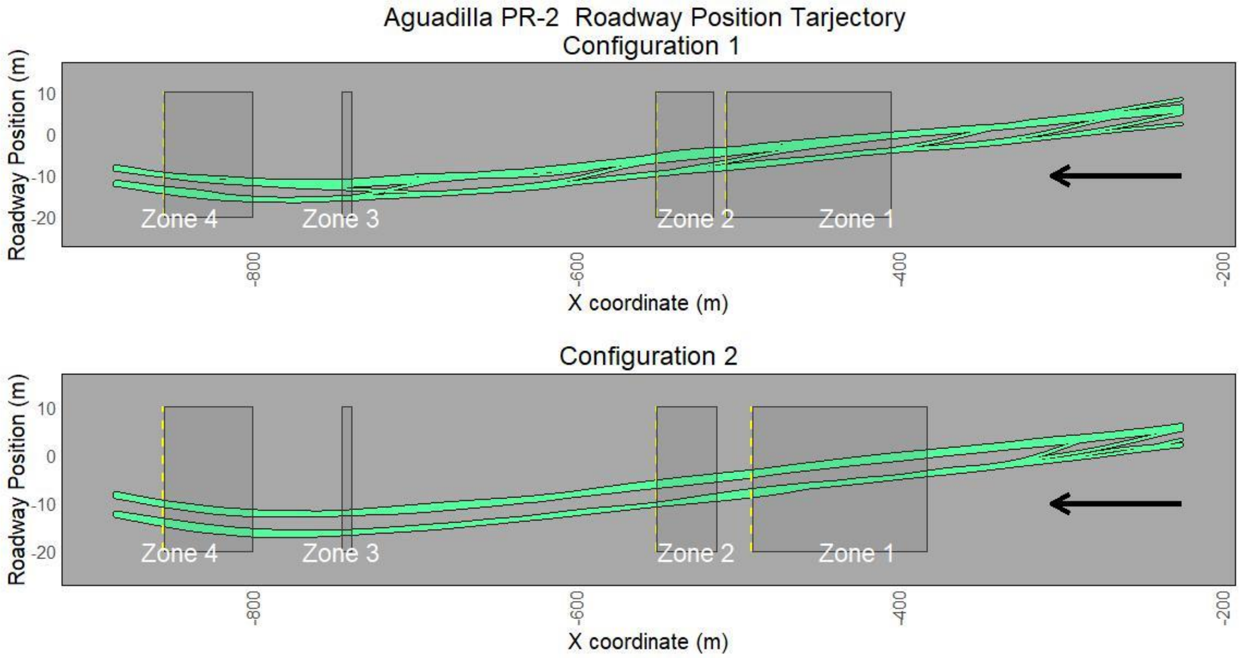


Figure C. 5 - Scenario 5 subjects' position by configuration

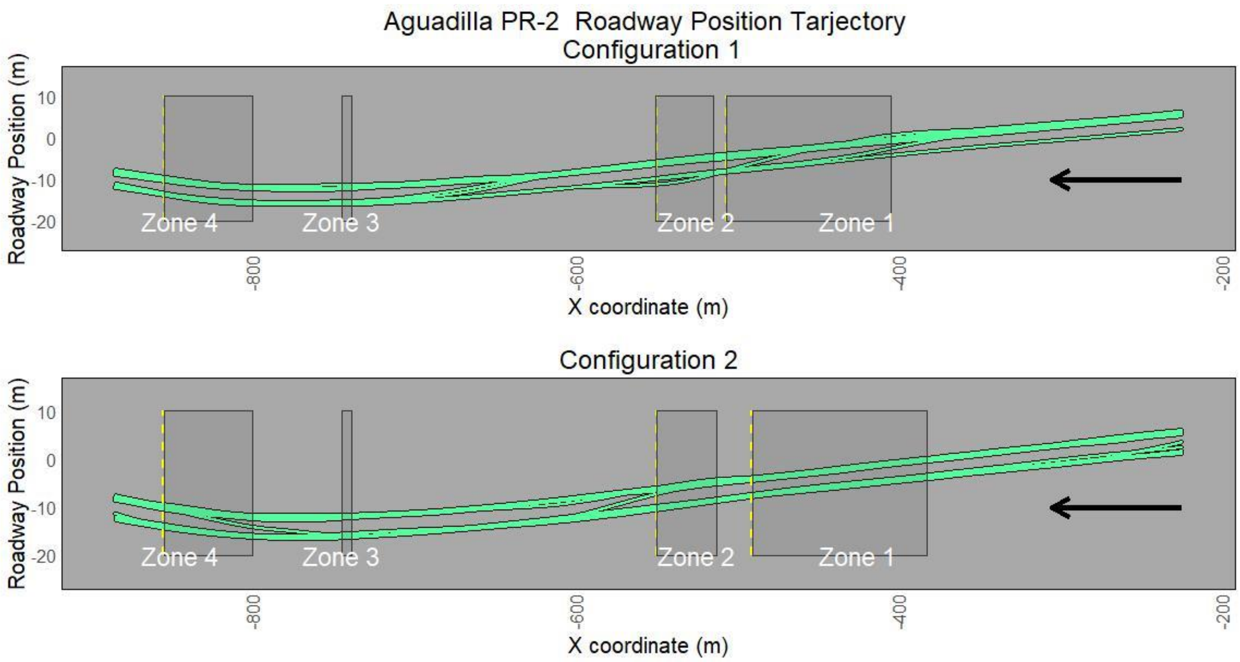


Figure C. 6 - Scenario 6 subjects' position by configuration

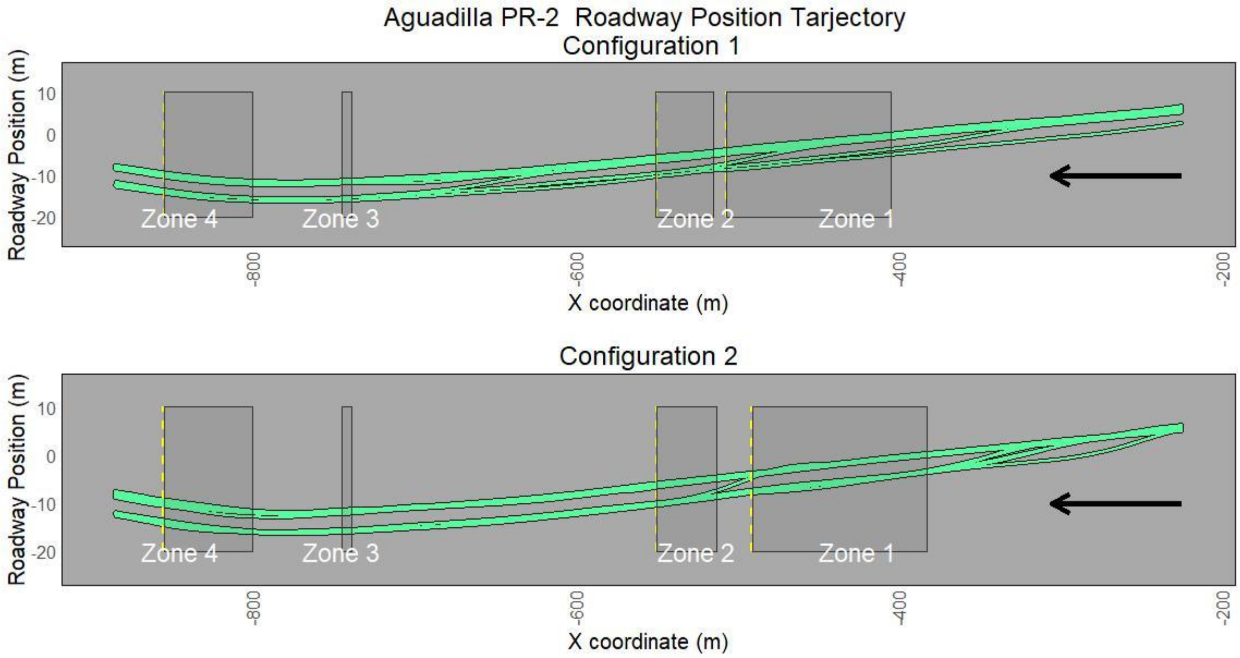


Figure C. 7 - Scenario 7 subjects' position by configuration

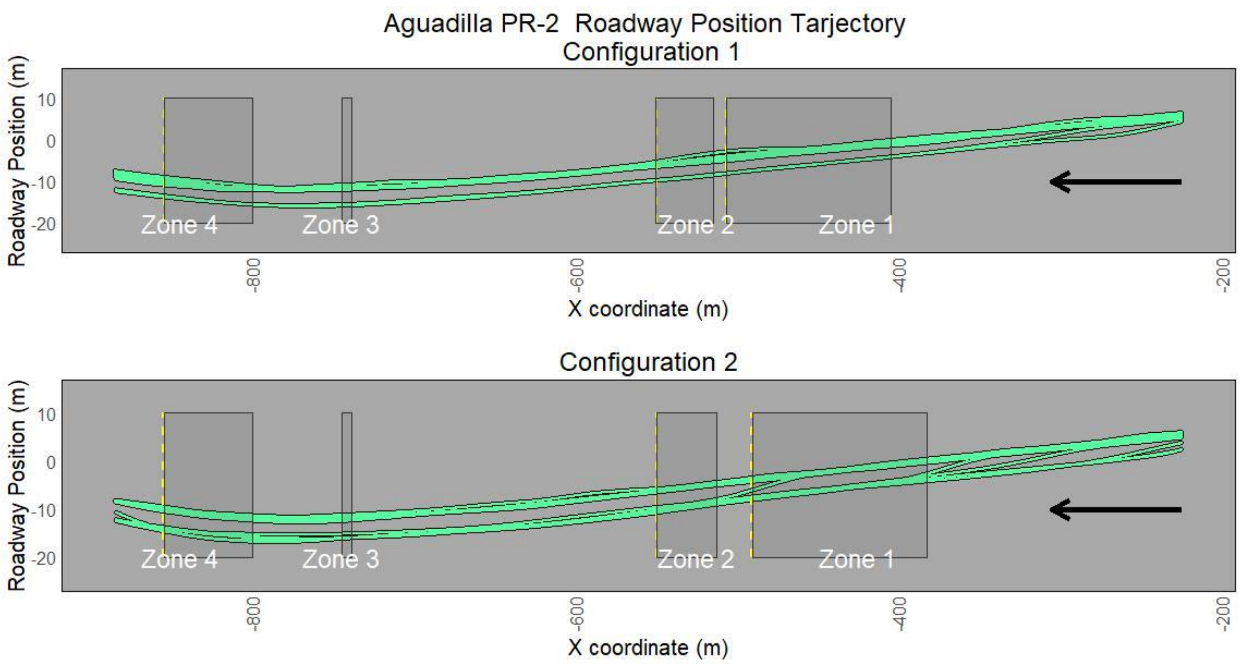


Figure C. 8 - Scenario 8 subjects' position by configuration

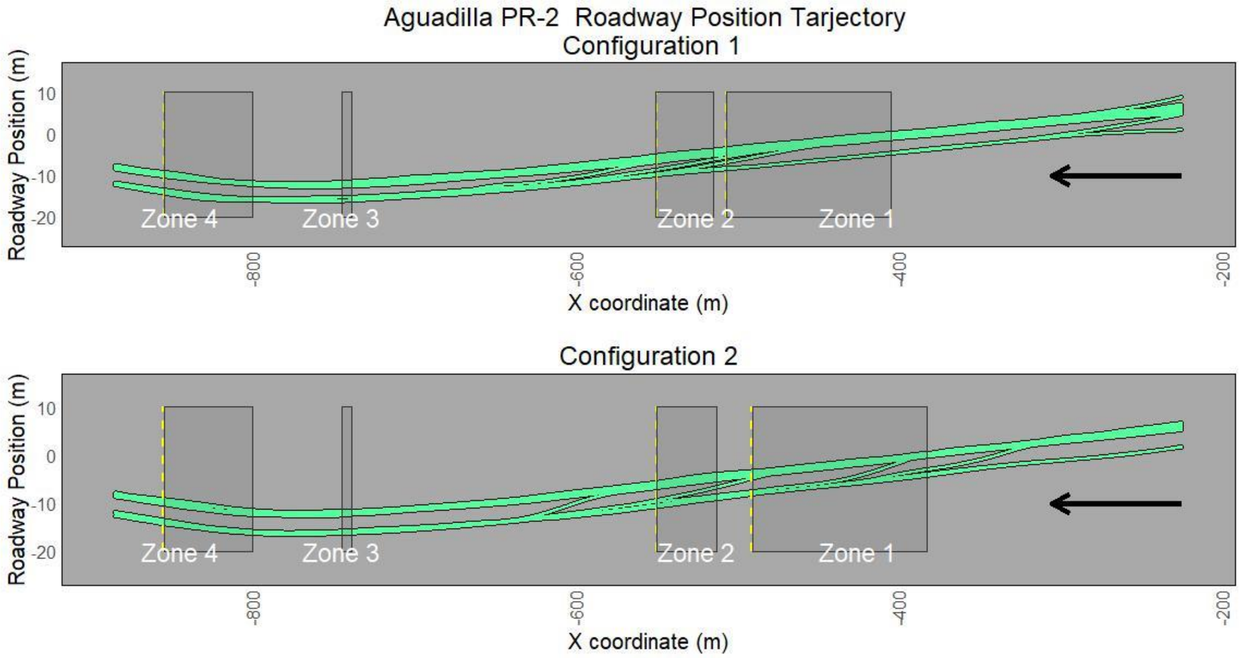


Figure C. 9 - Scenario 9 subjects' position by configuration

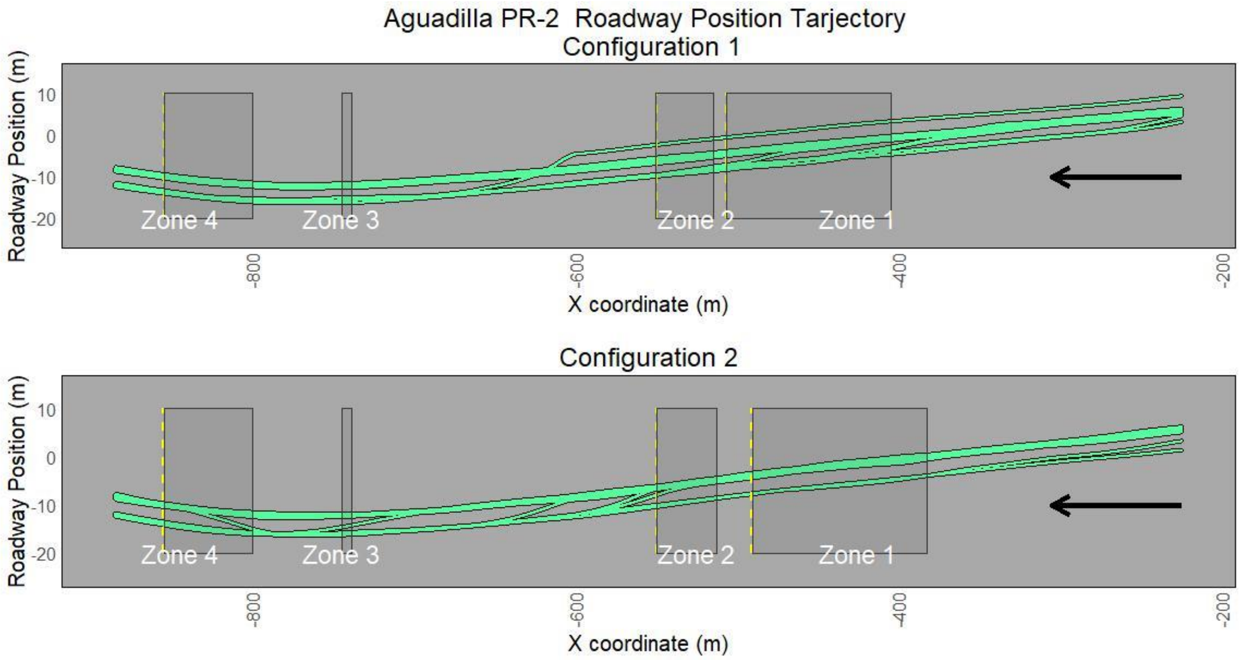


Figure C. 10 - Scenario 10 subjects' position by configuration

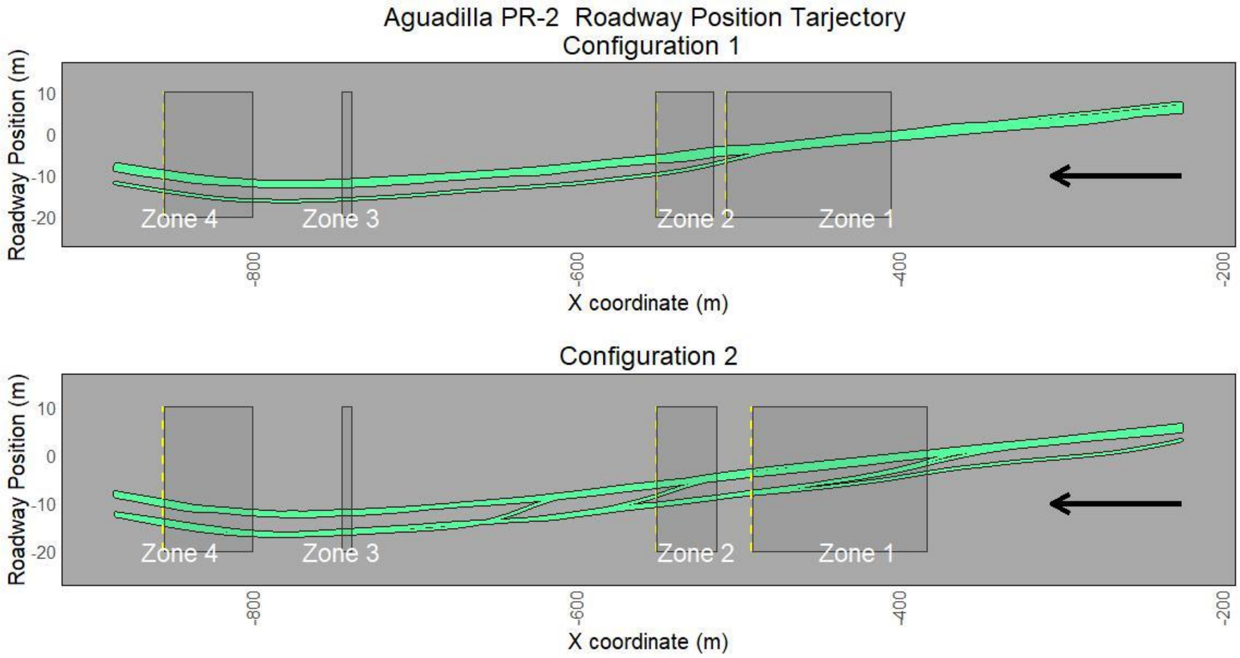


Figure C. 11 - Scenario 11 subjects' position by configuration

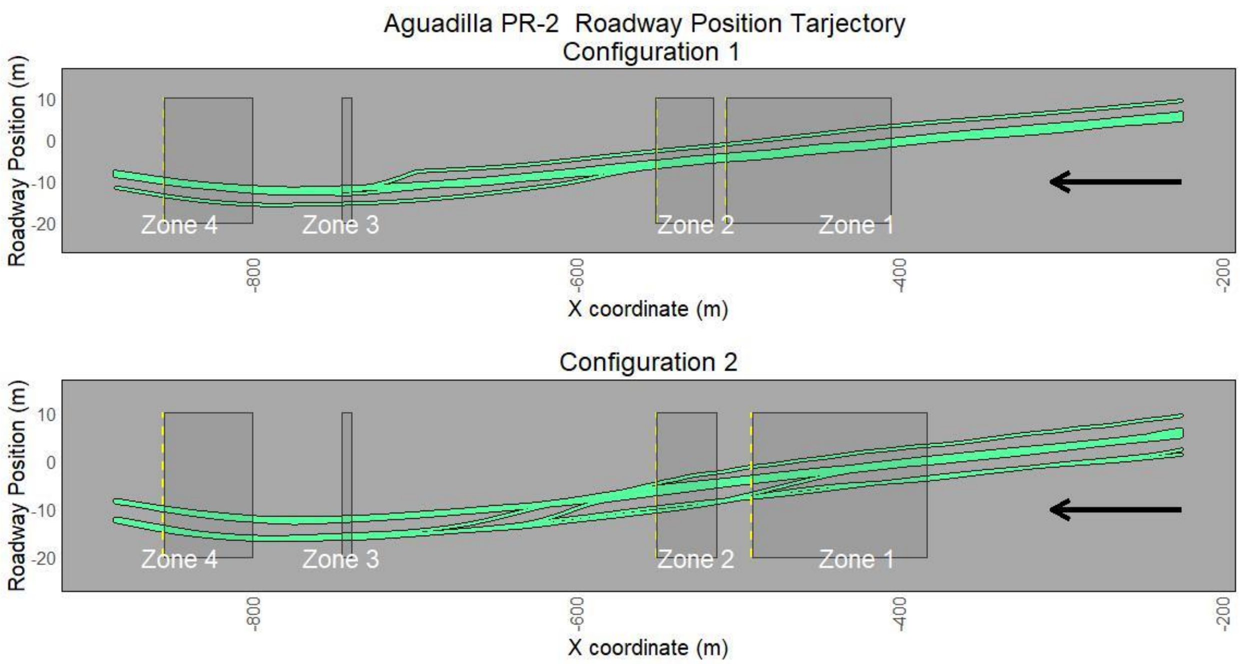


Figure C. 12 - Scenario 12 subjects' position by configuration

Appendix D: S.U. Samuel Adams Acceleration Noise

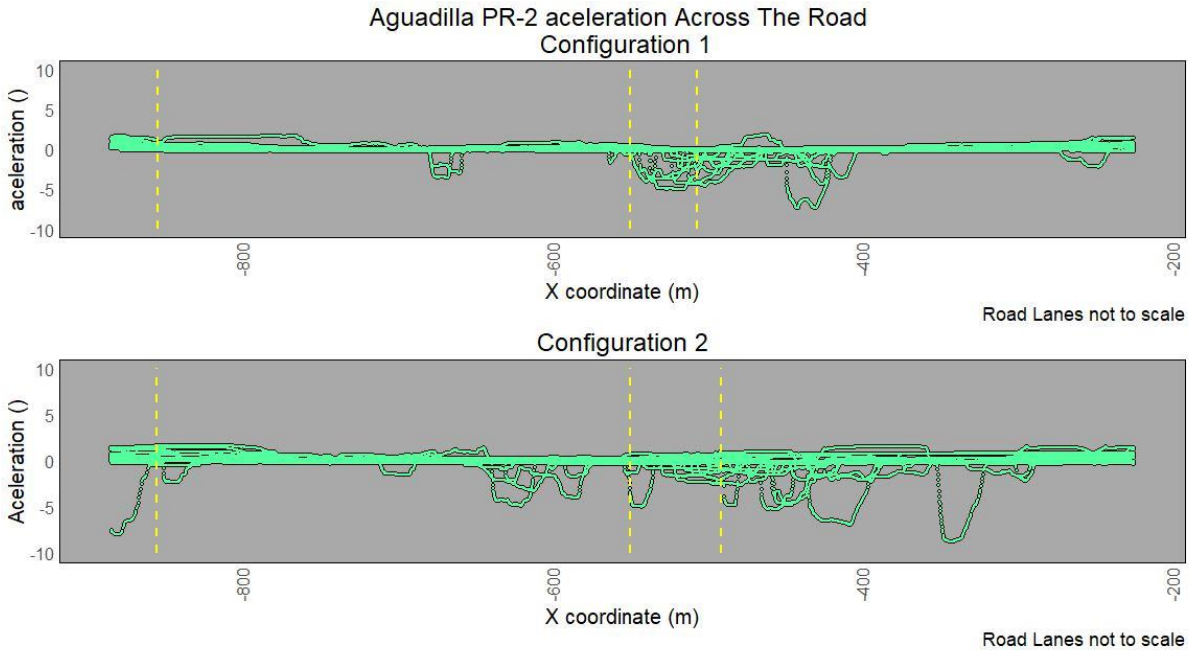


Figure D. 1 - Scenario 1 subjects' acceleration noise by configuration

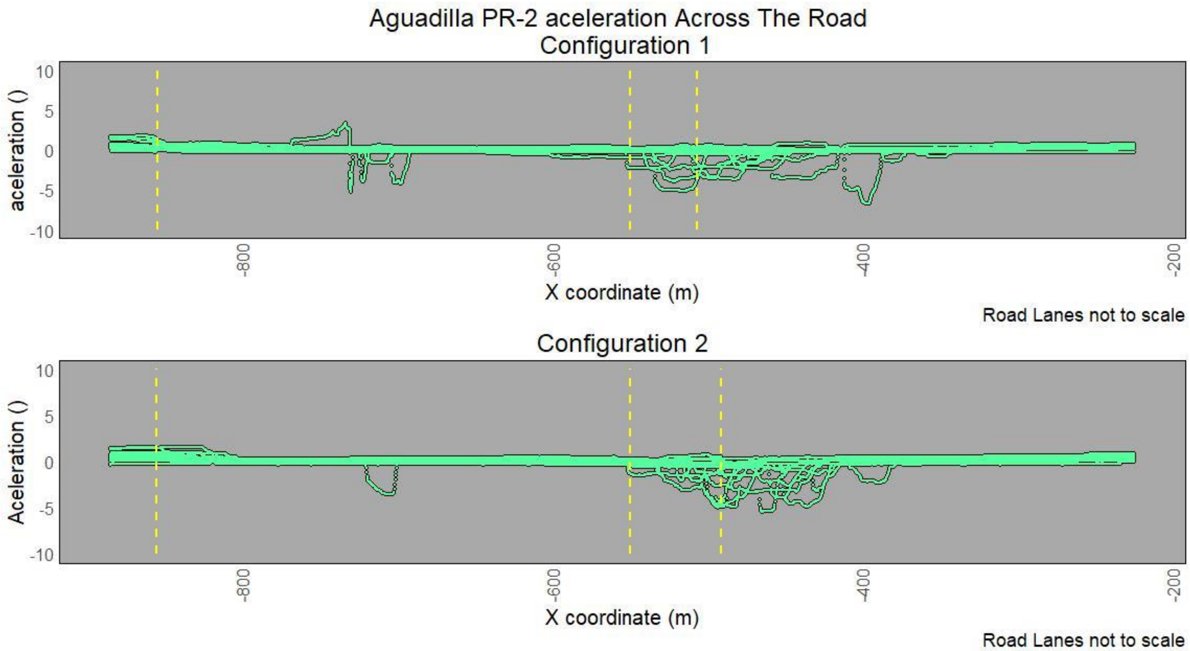


Figure D. 2 - Scenario 2 subjects' acceleration noise by configuration

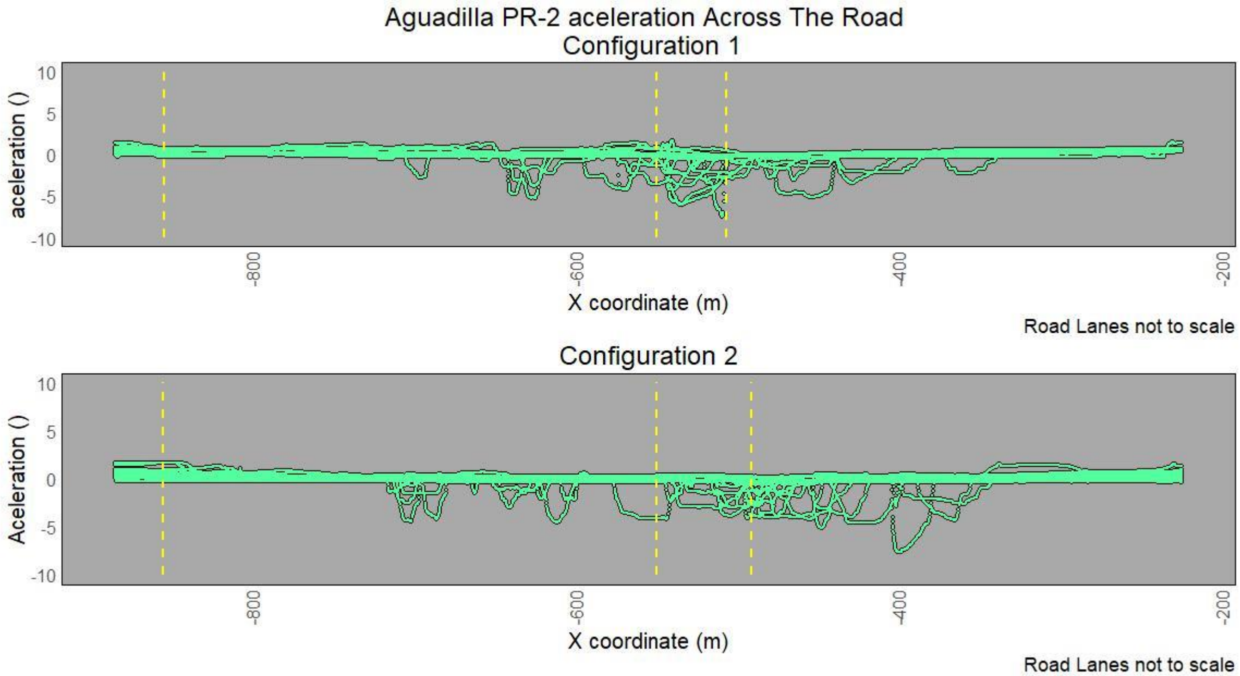


Figure D. 3 - Scenario 3 subjects' acceleration noise by configuration

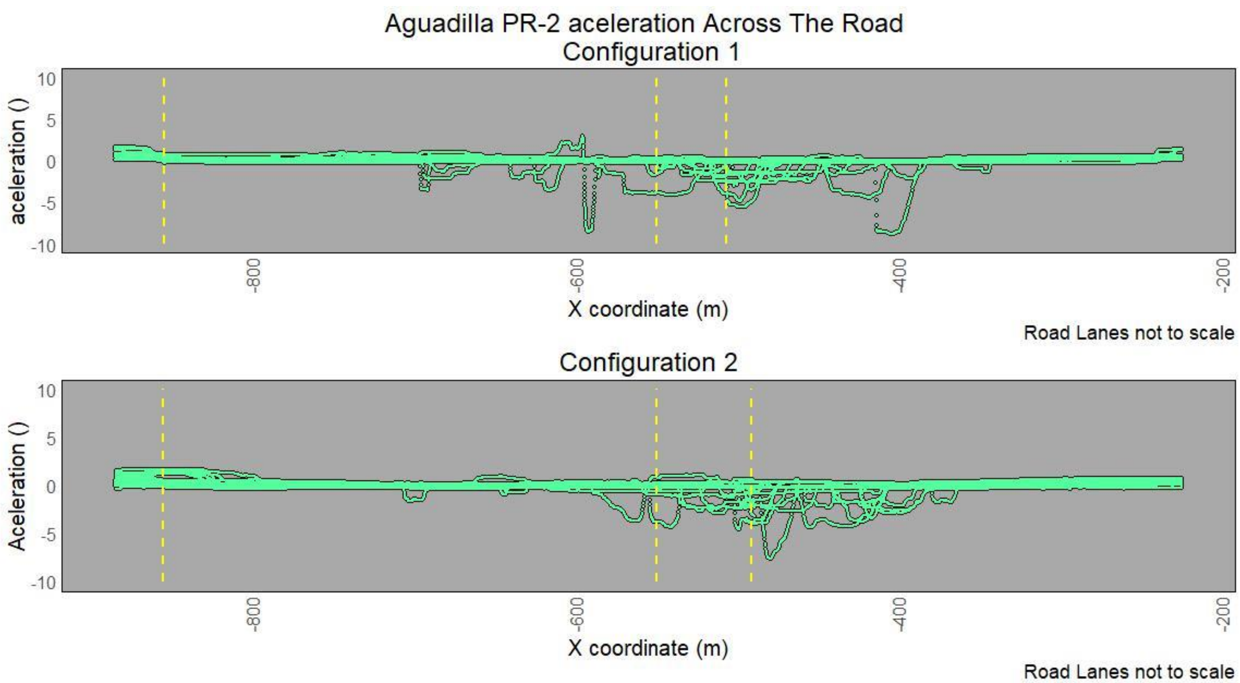


Figure D. 4 - Scenario 4 subjects' acceleration noise by configuration

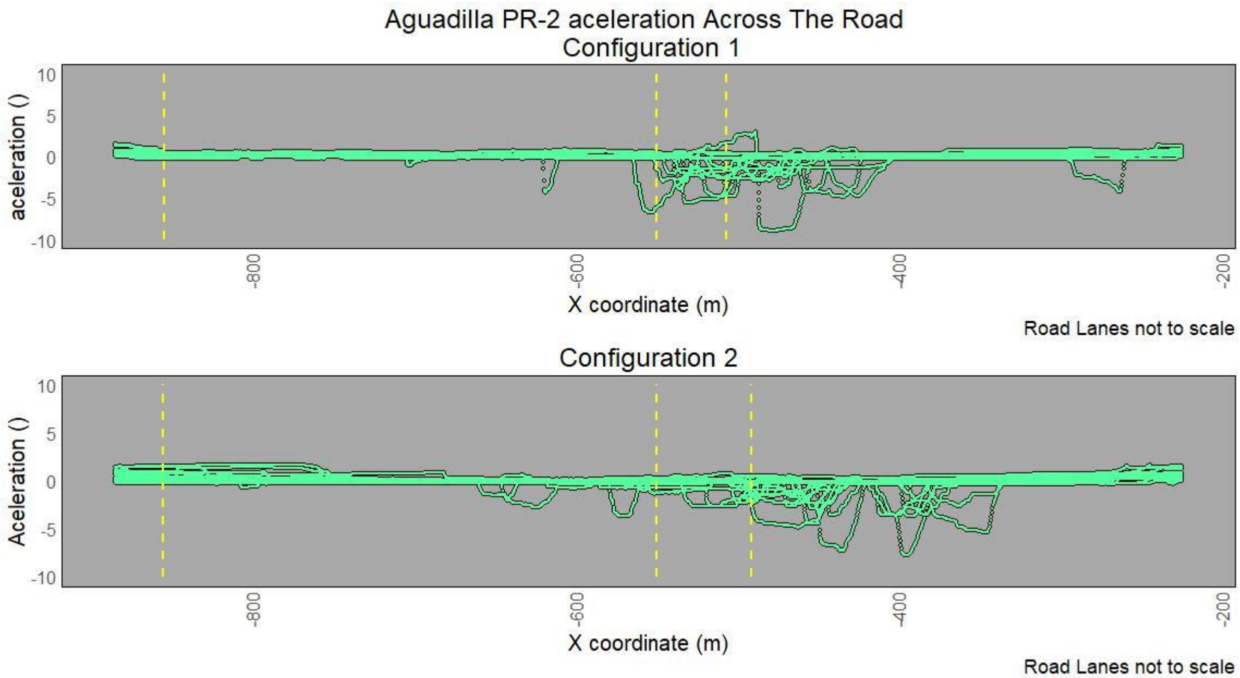


Figure D. 5 - Scenario 5 subjects' acceleration noise by configuration

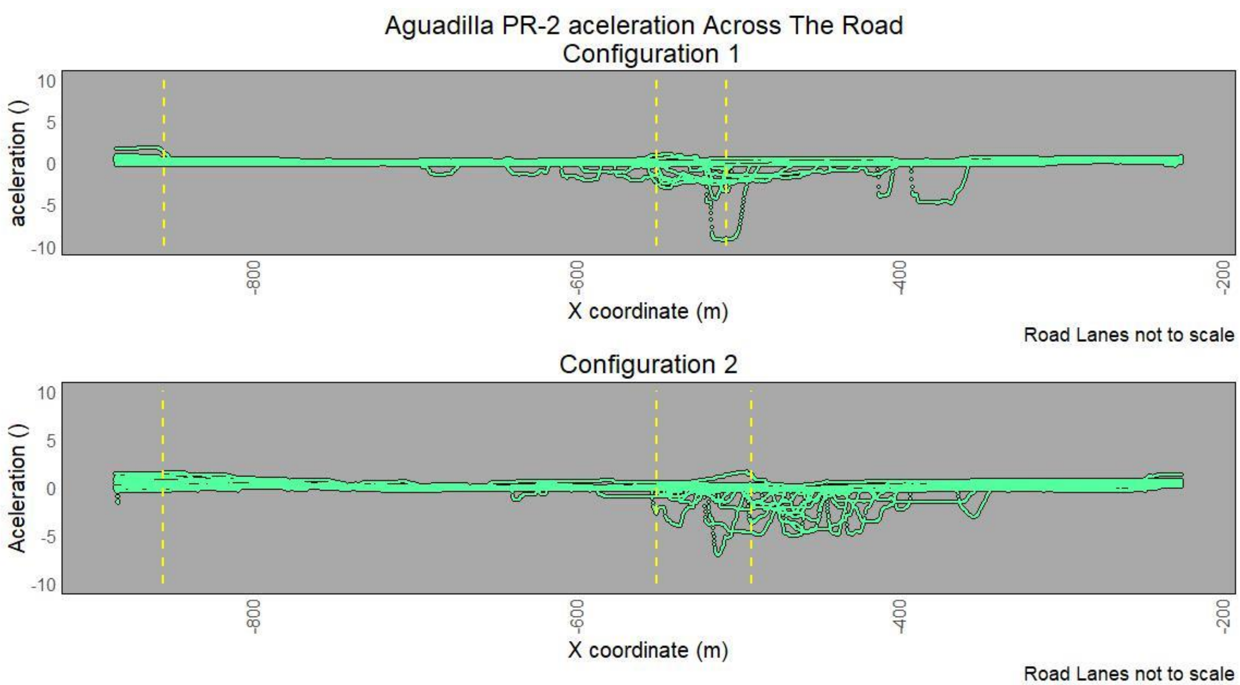


Figure D. 6 - Scenario 6 subjects' acceleration noise by configuration

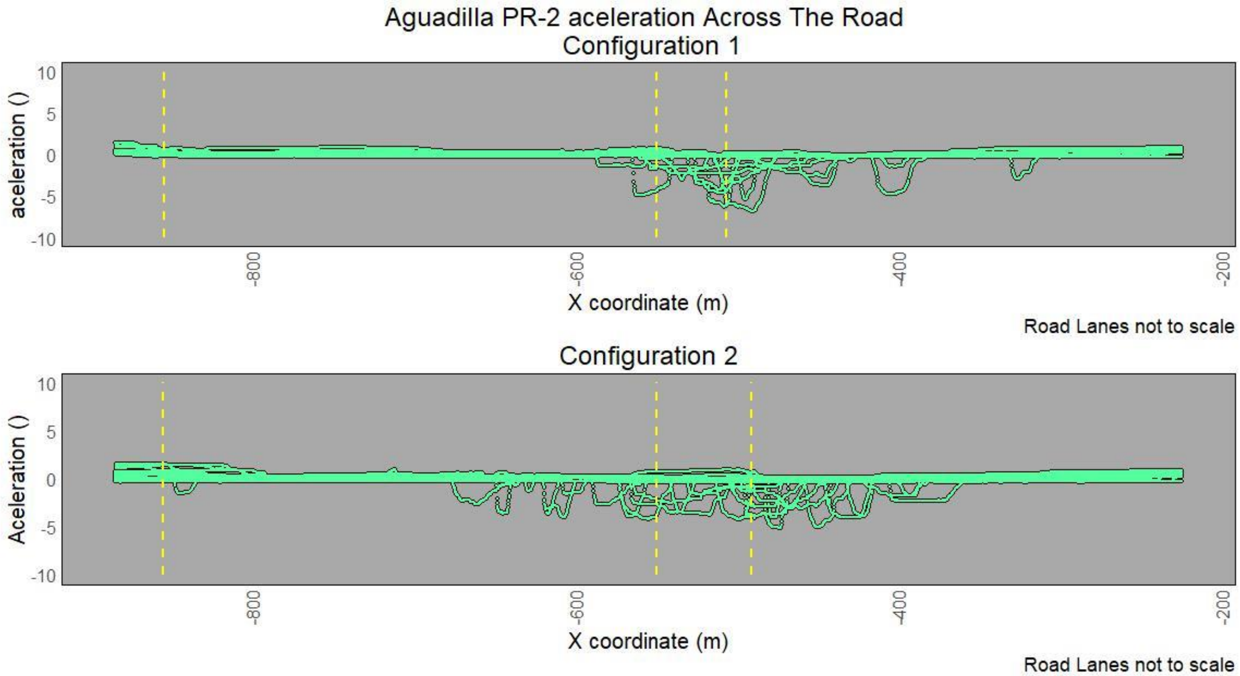


Figure D. 7 - Scenario 7 subjects' acceleration noise by configuration

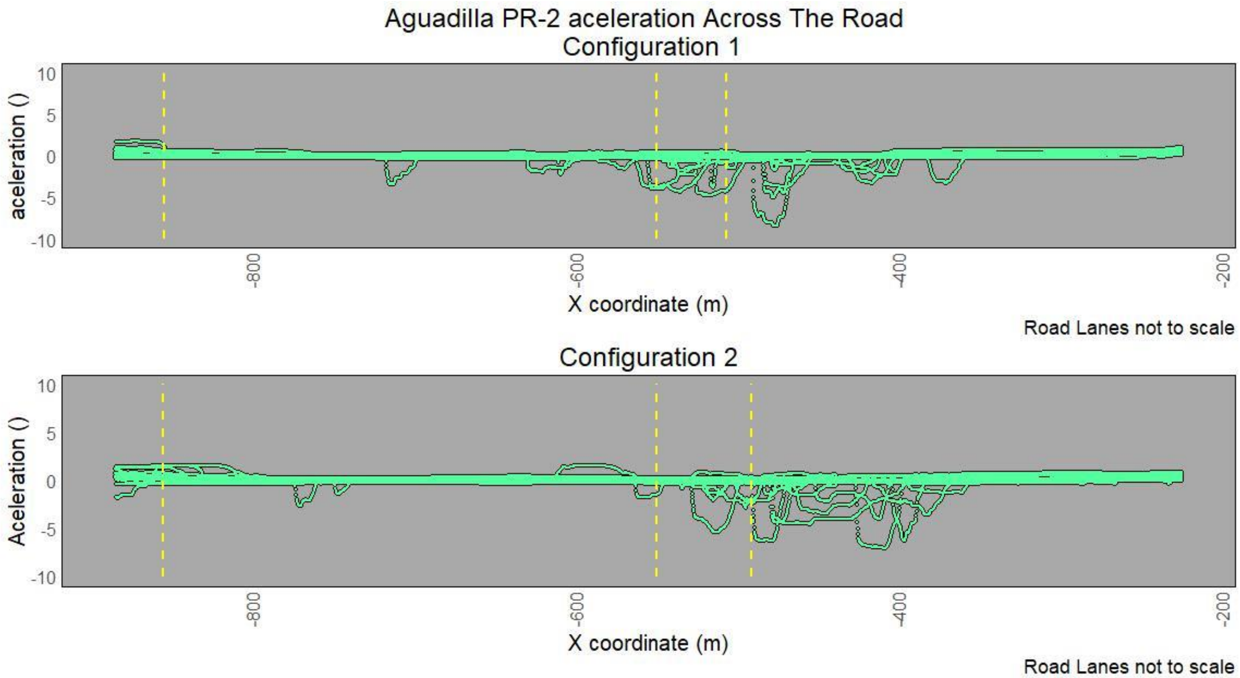


Figure D. 8 - Scenario 8 subjects' acceleration noise by configuration

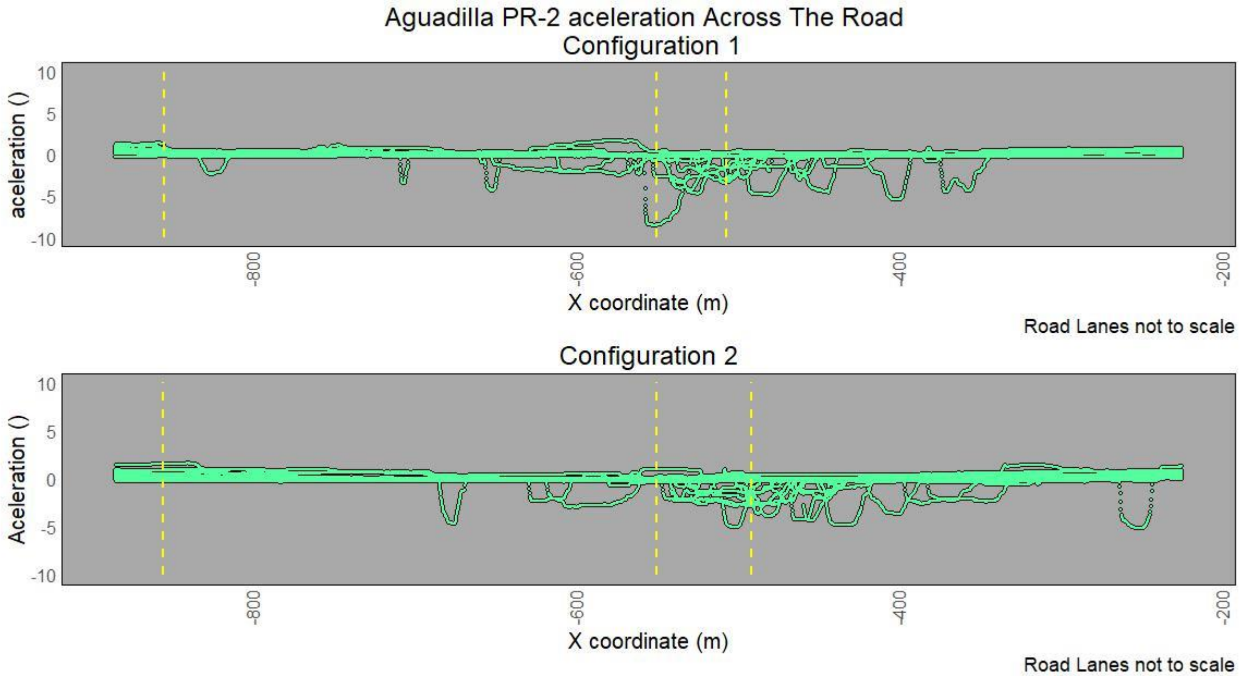


Figure D. 9 - Scenario 9 subjects' acceleration noise by configuration

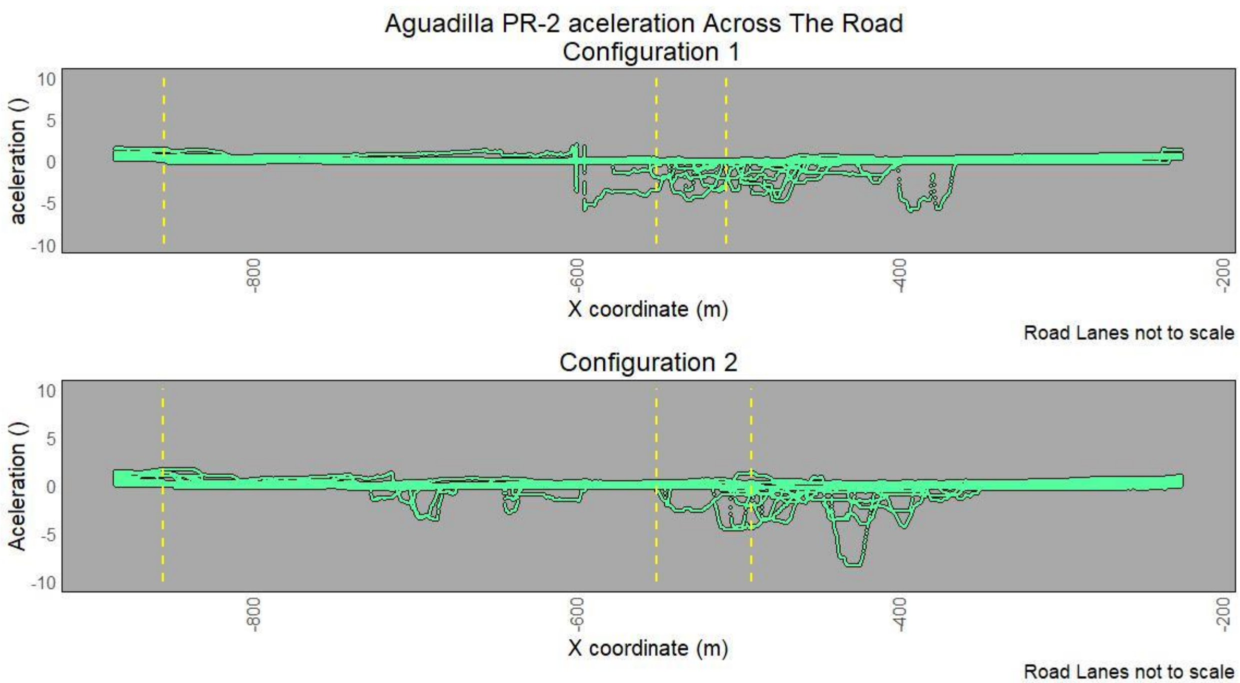


Figure D. 10 - Scenario 10 subjects' acceleration noise by configuration

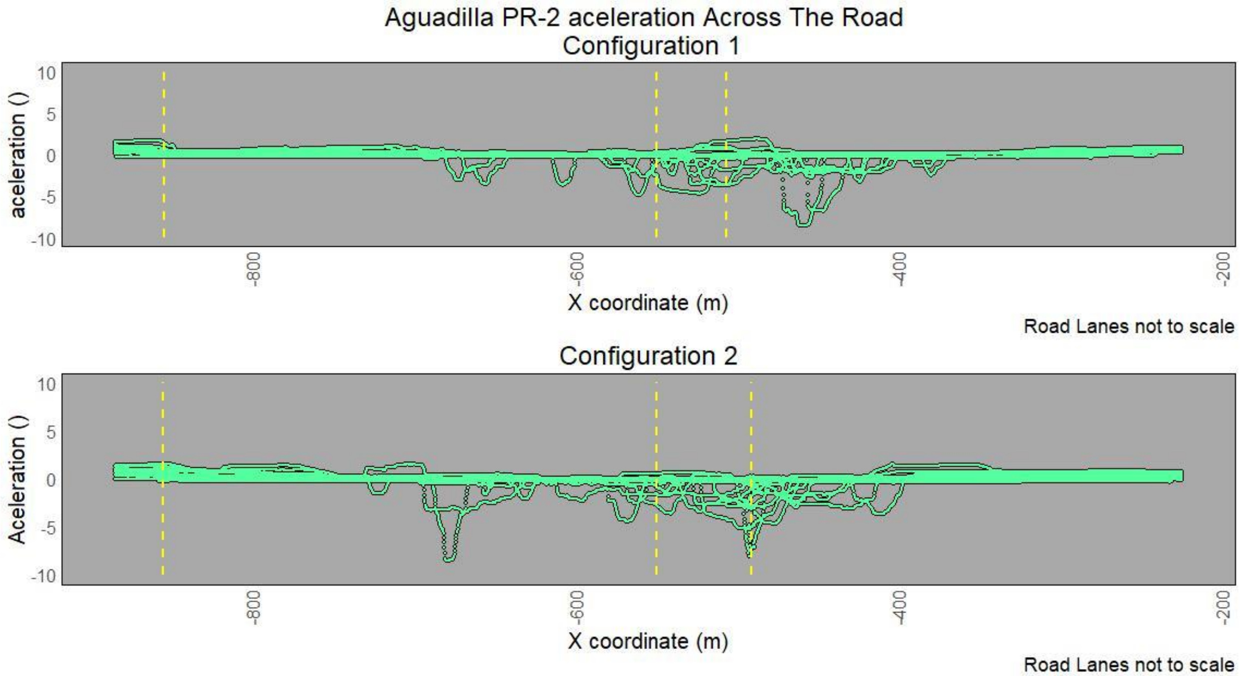


Figure D. 11 - Scenario 11 subjects' acceleration noise by configuration

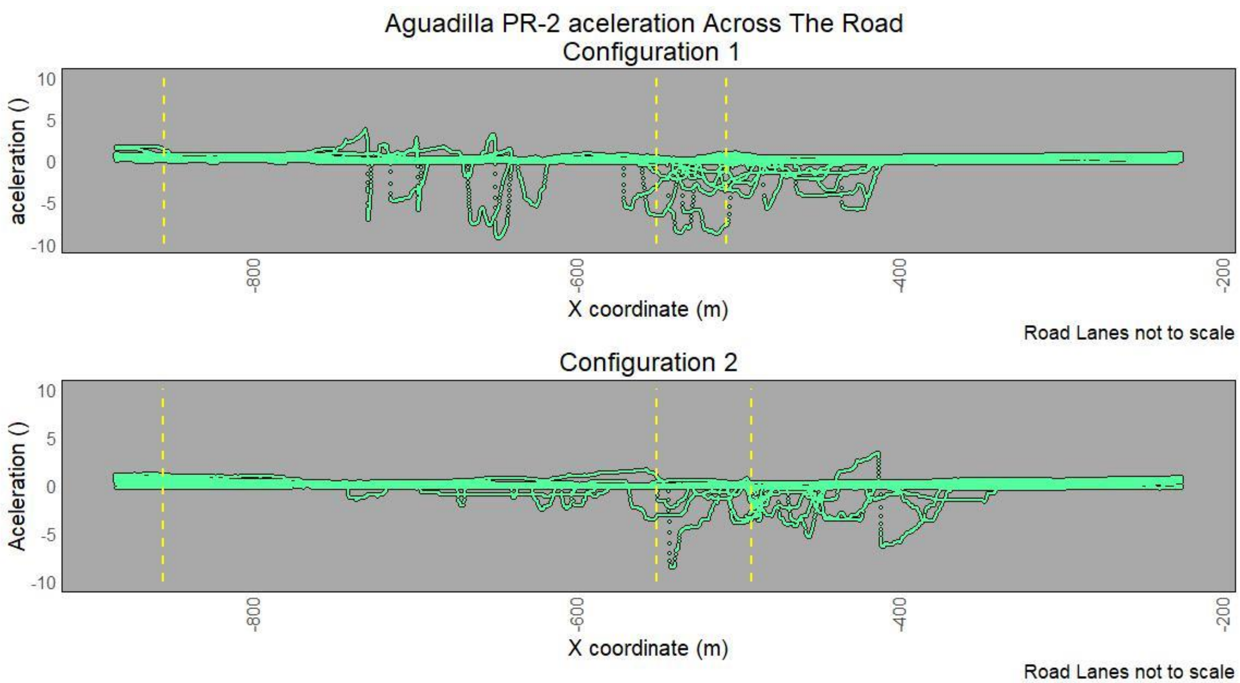


Figure D. 12 - Scenario 12 subjects' acceleration noise by configuration

Appendix E: Franklin D. Roosevelt Pedestrian Time to Collision

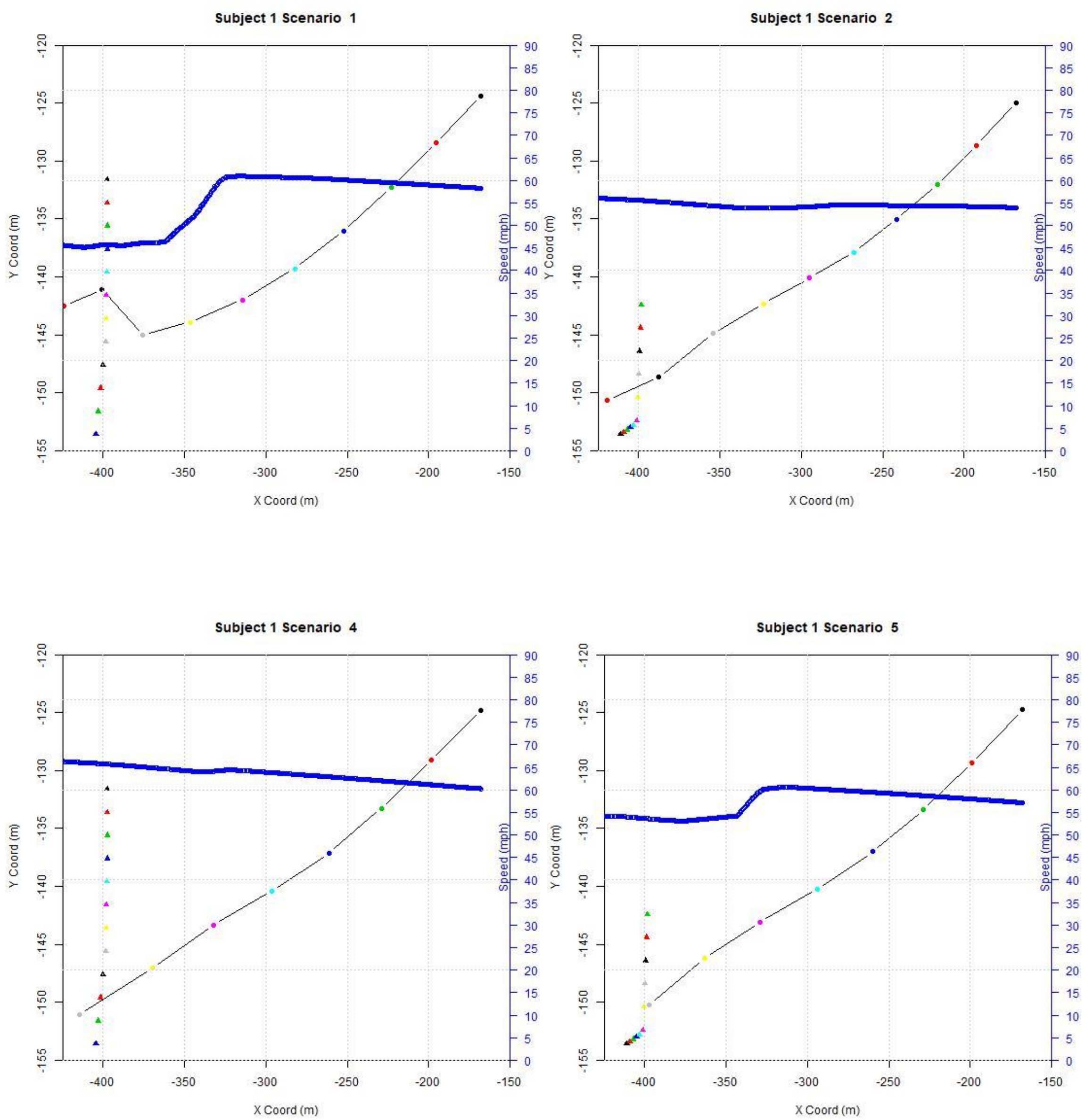


Figure E. 1 - Position and speed profiles of Subject 1

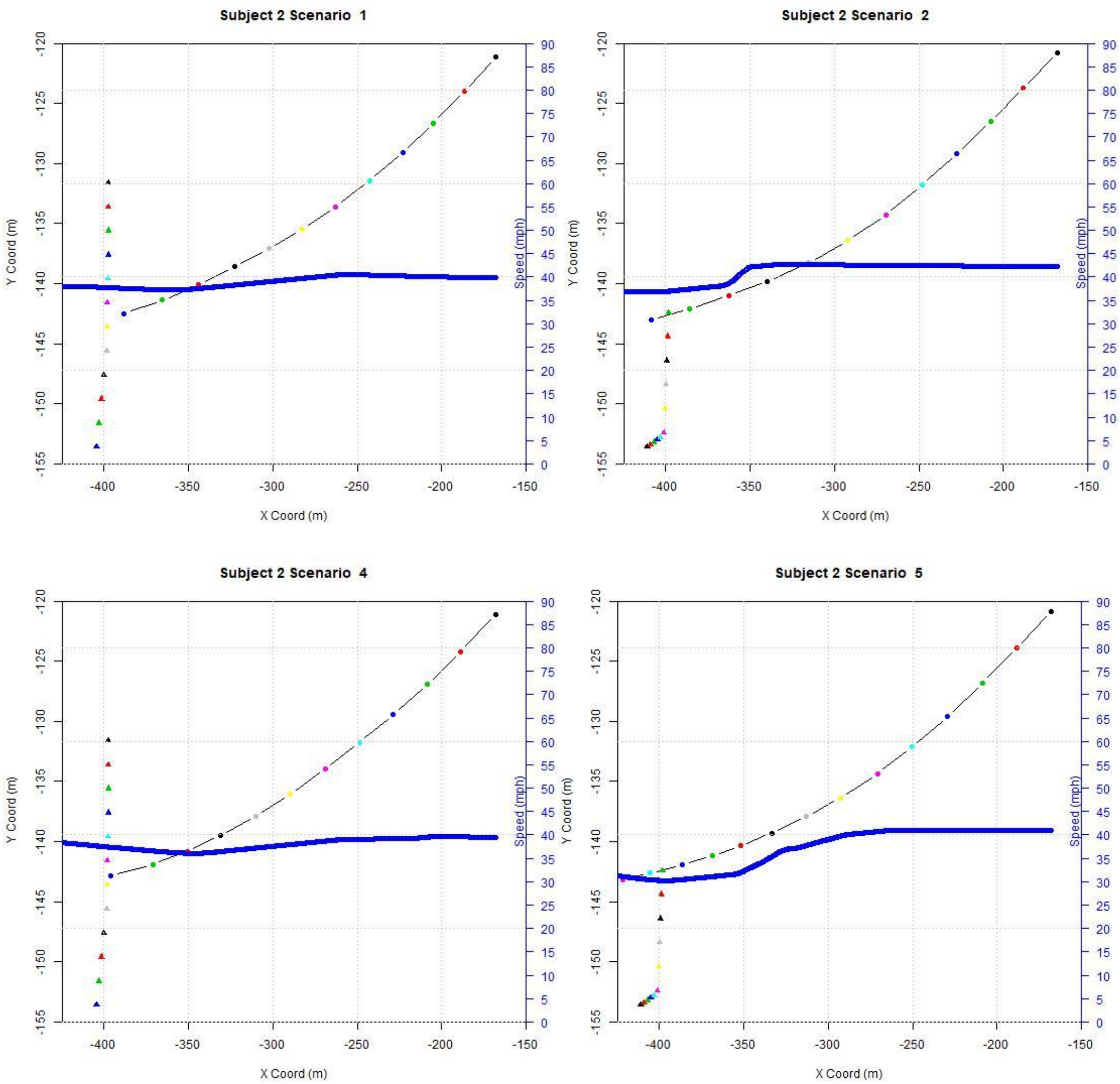


Figure E. 2 - Position and speed profiles of Subject 2

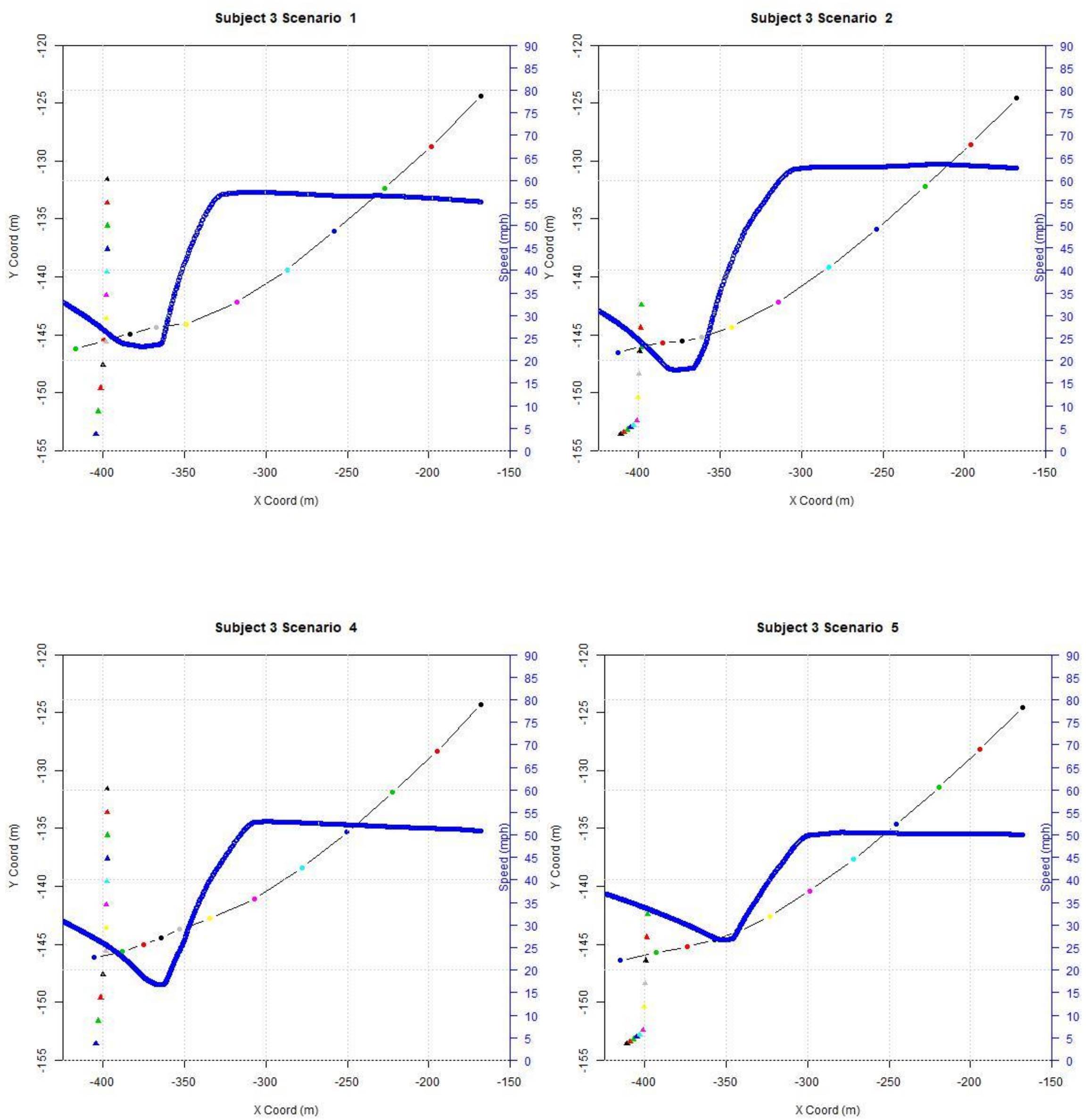


Figure E. 3 - Position and speed profiles of Subject 3

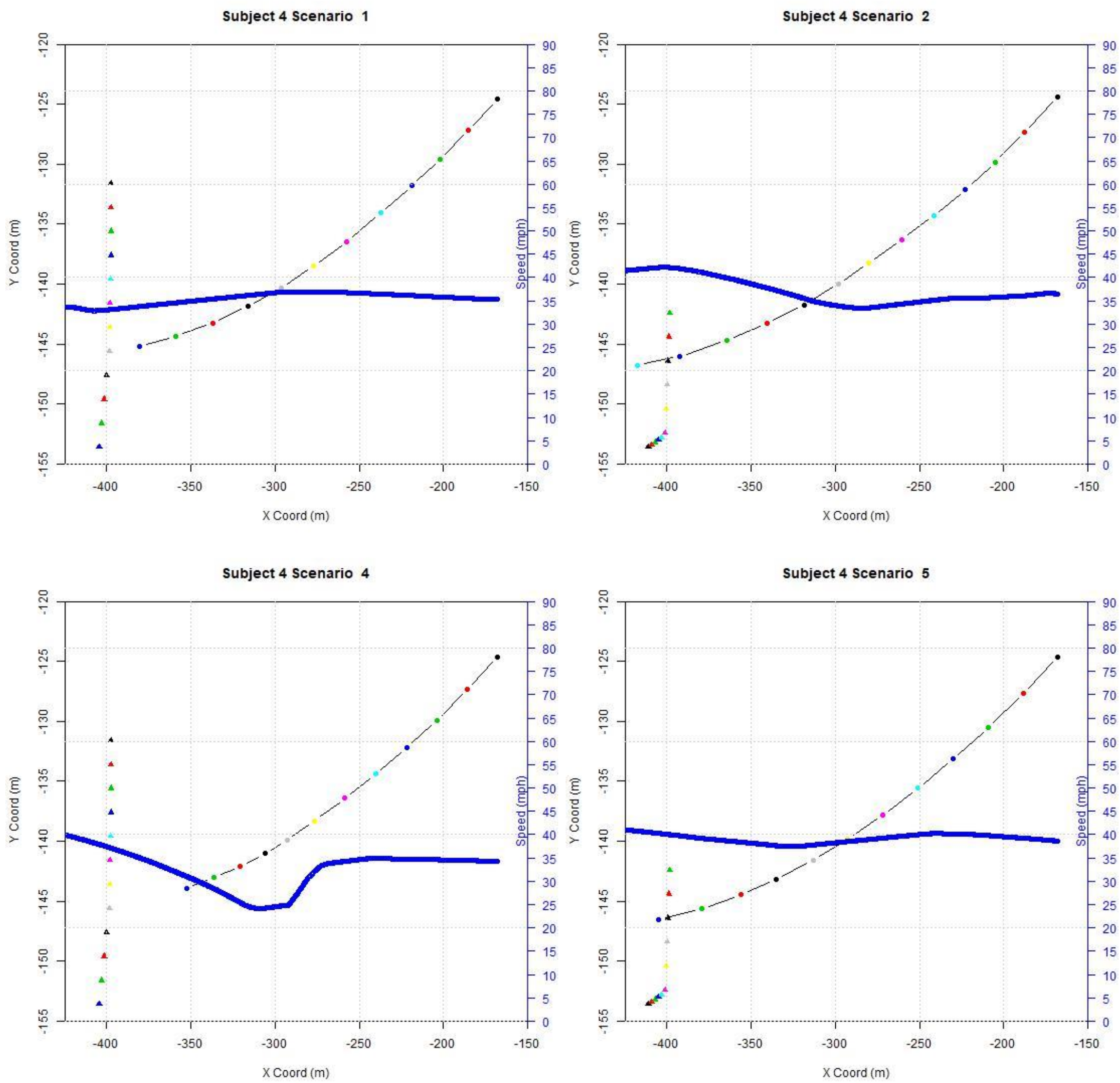


Figure E. 4 - Position and speed profiles of Subject 4

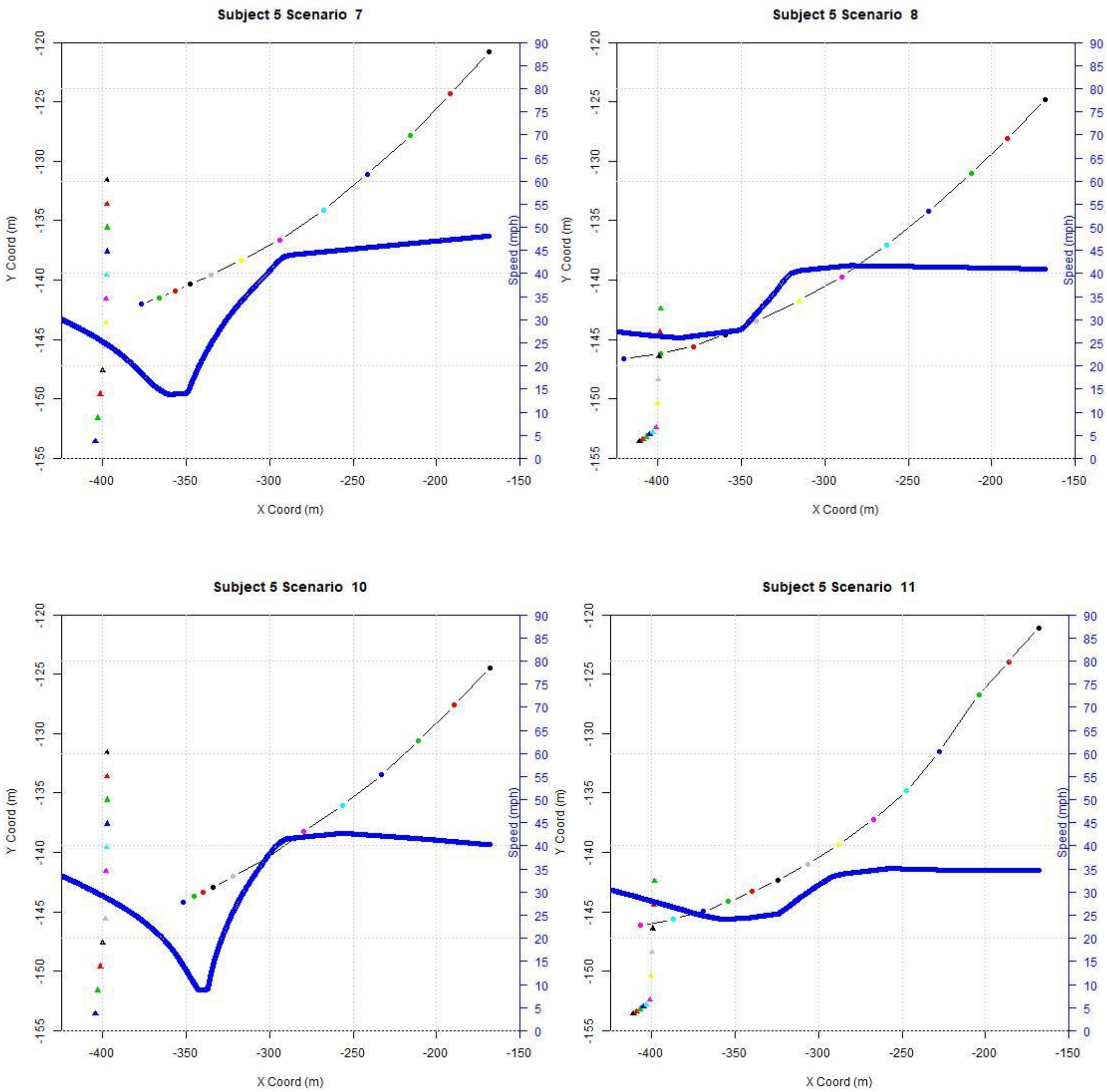


Figure E. 5 - Position and speed profiles of Subject 5

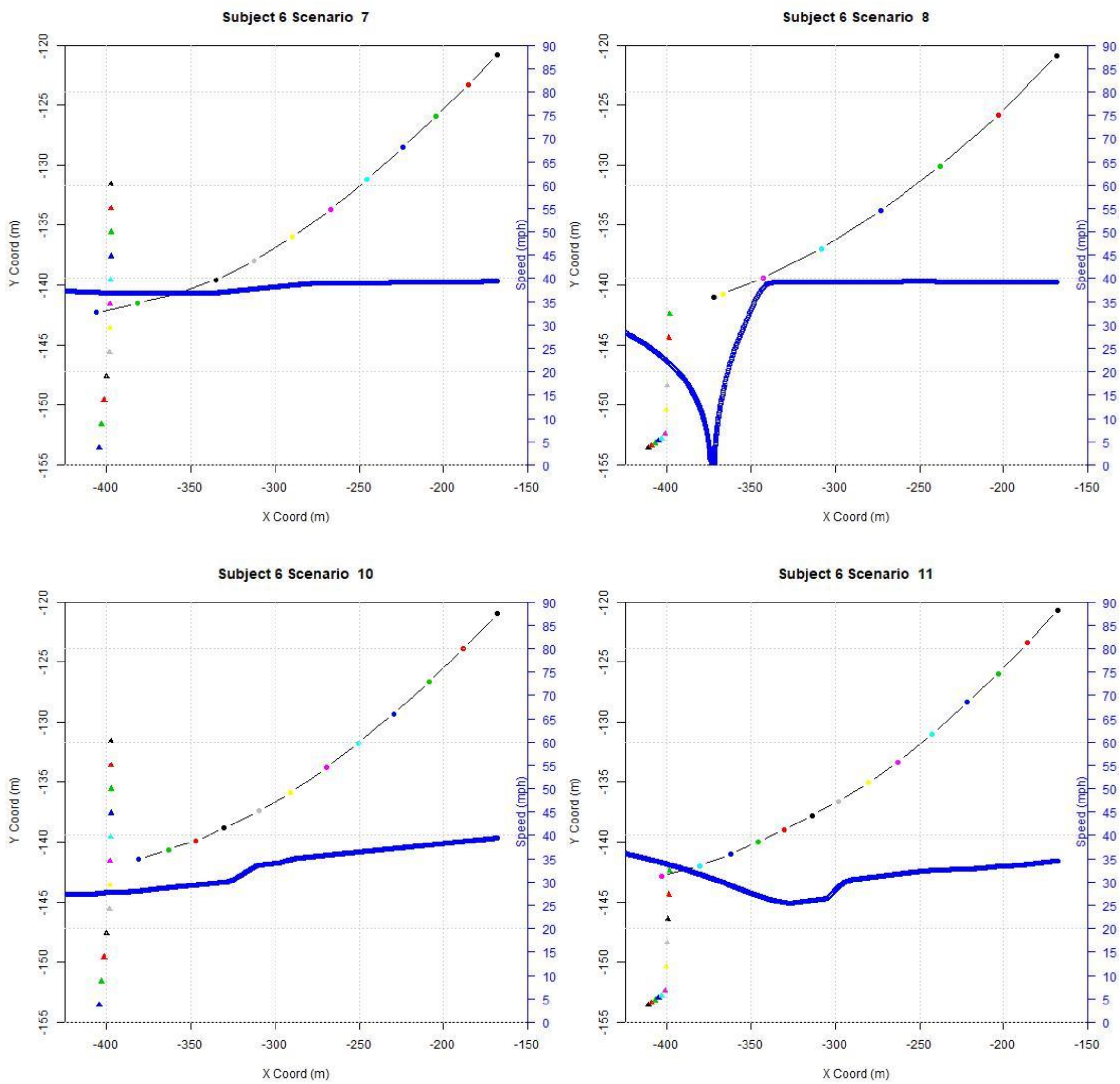


Figure E. 6 - Position and speed profiles of Subject 6

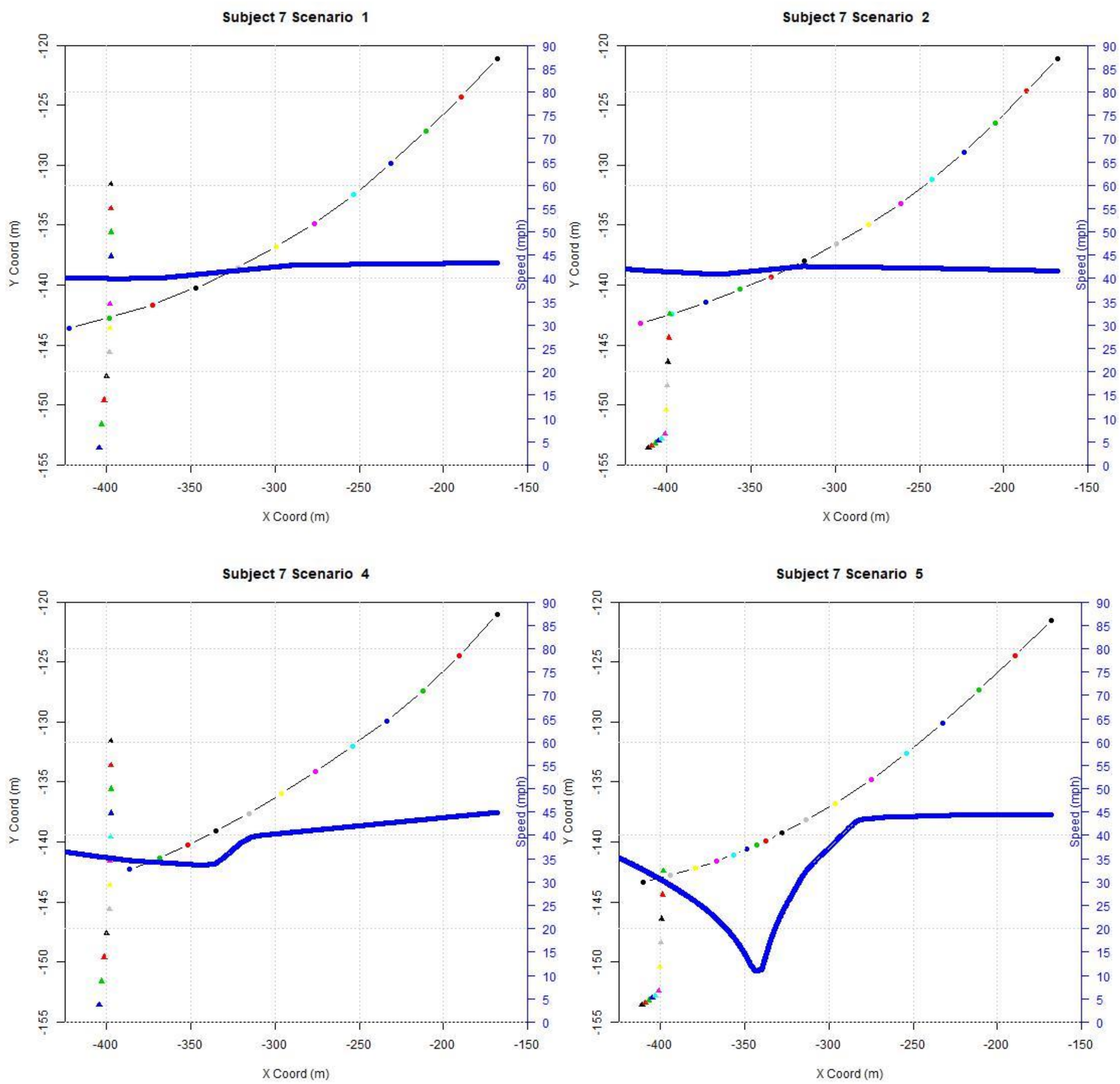


Figure E. 7 - Position and speed profiles of Subject 7

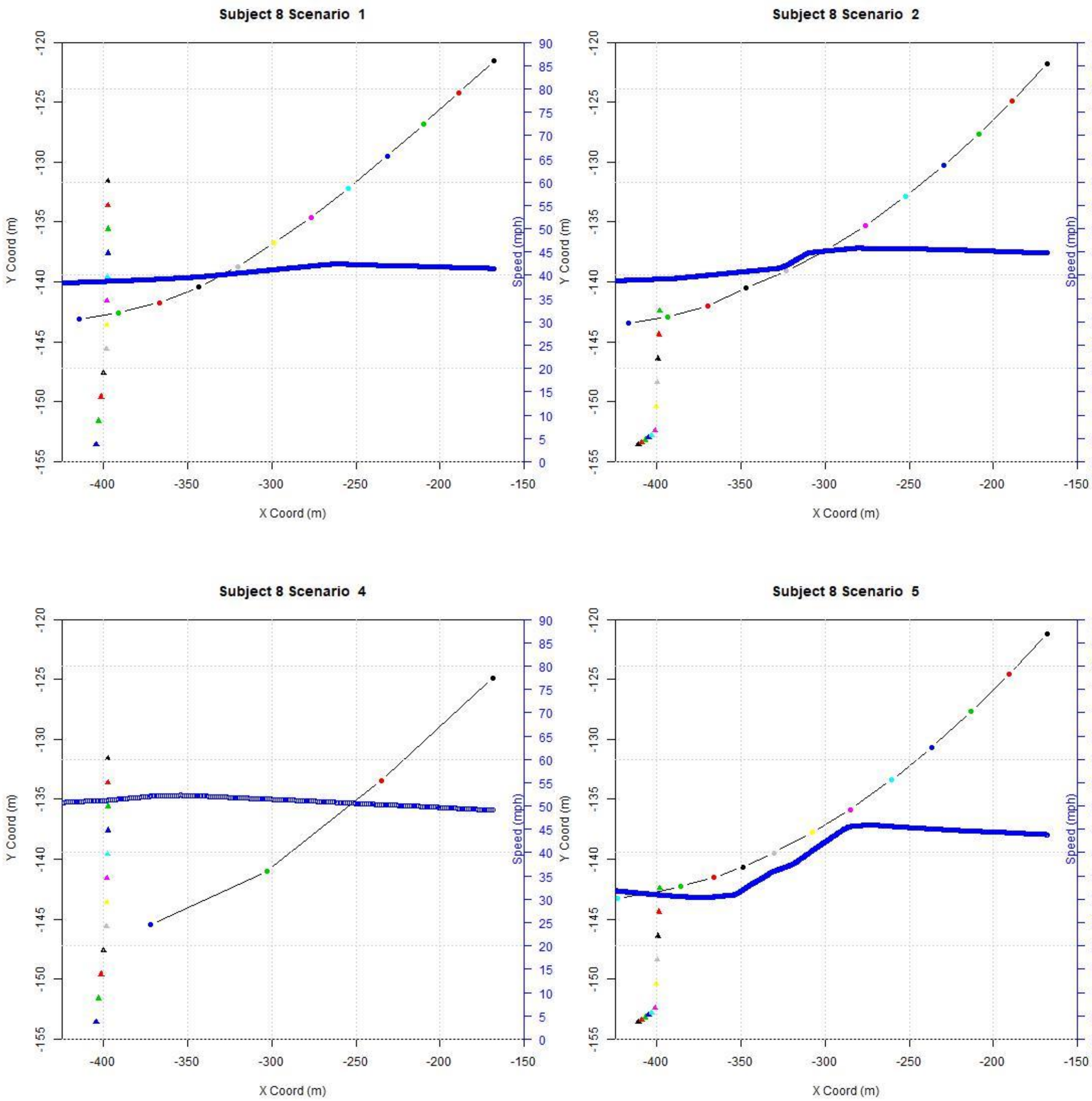


Figure E. 8 - Position and speed profiles of Subject 8

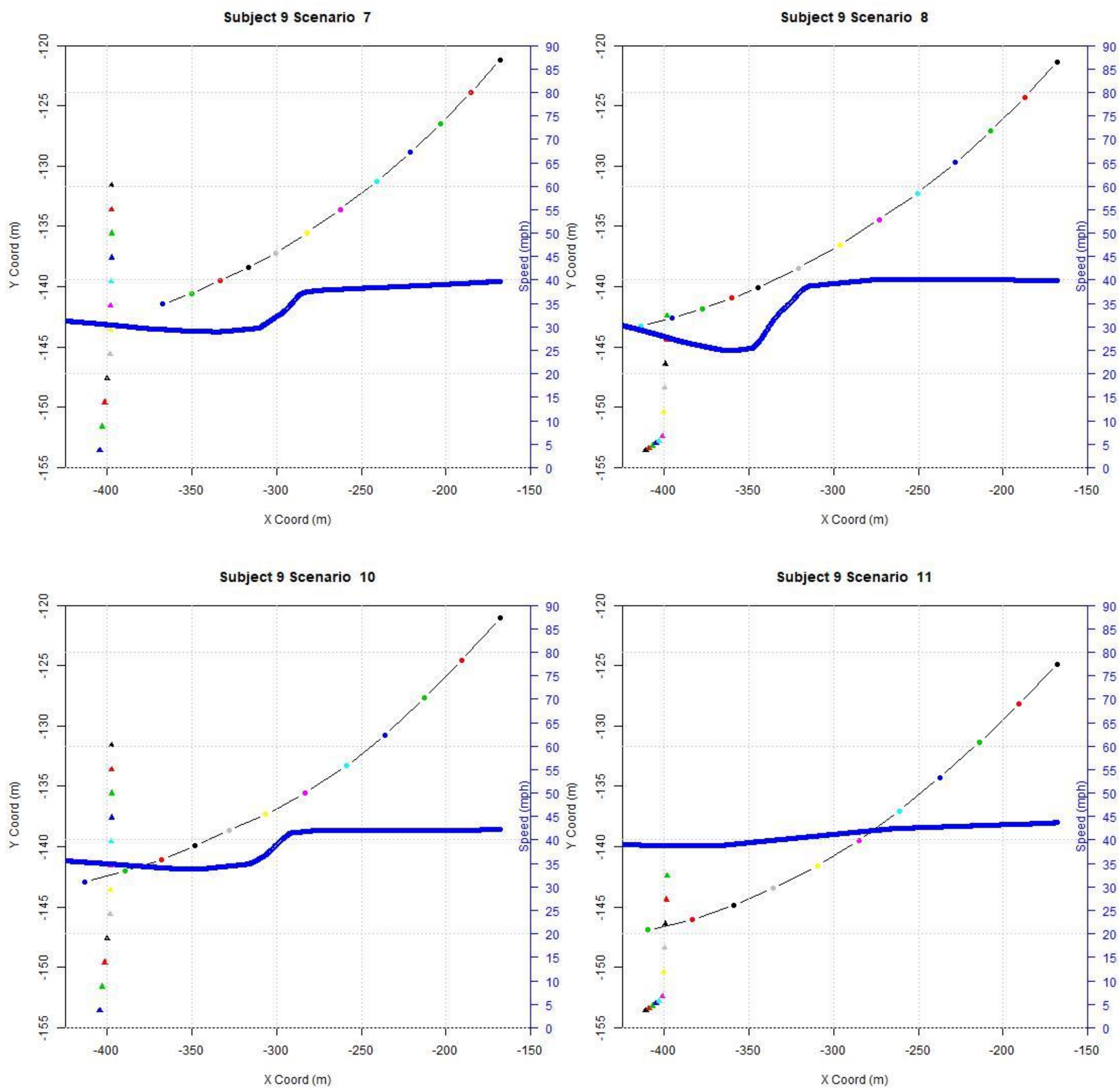


Figure E. 9 - Position and speed profiles of Subject 9

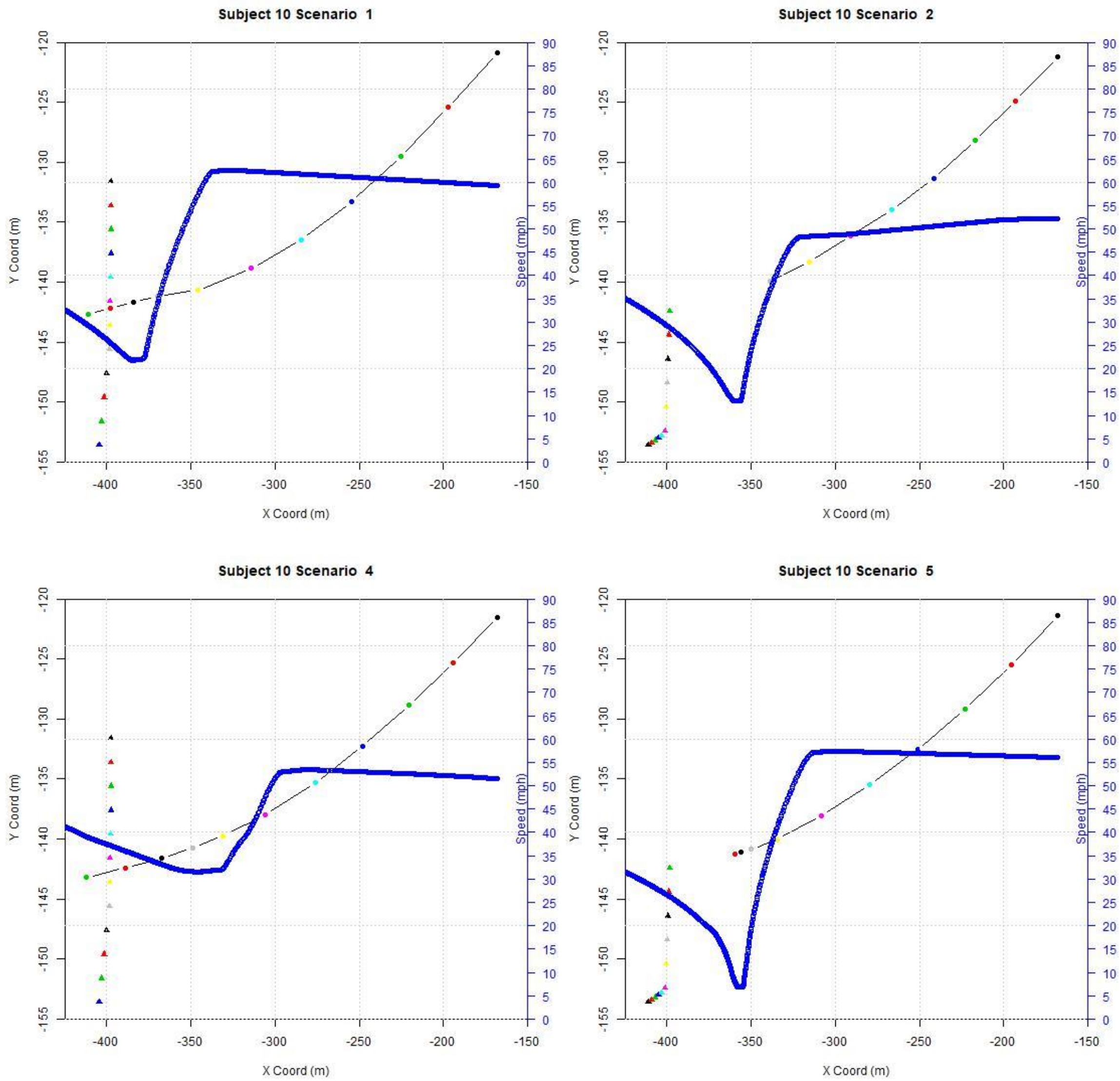


Figure E. 10 - Position and speed profiles of Subject 10

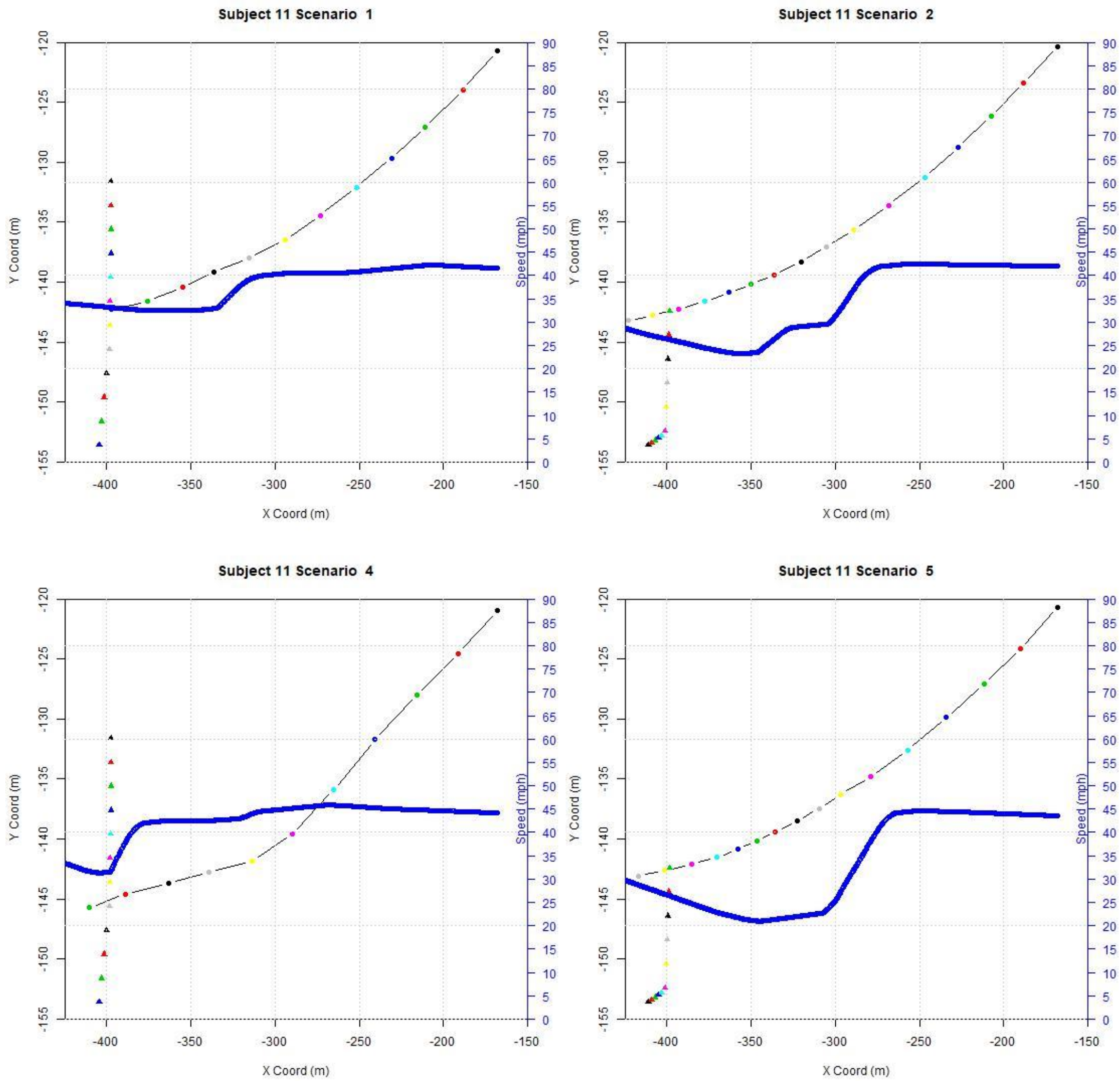


Figure E. 11 - Position and speed profiles of Subject 11

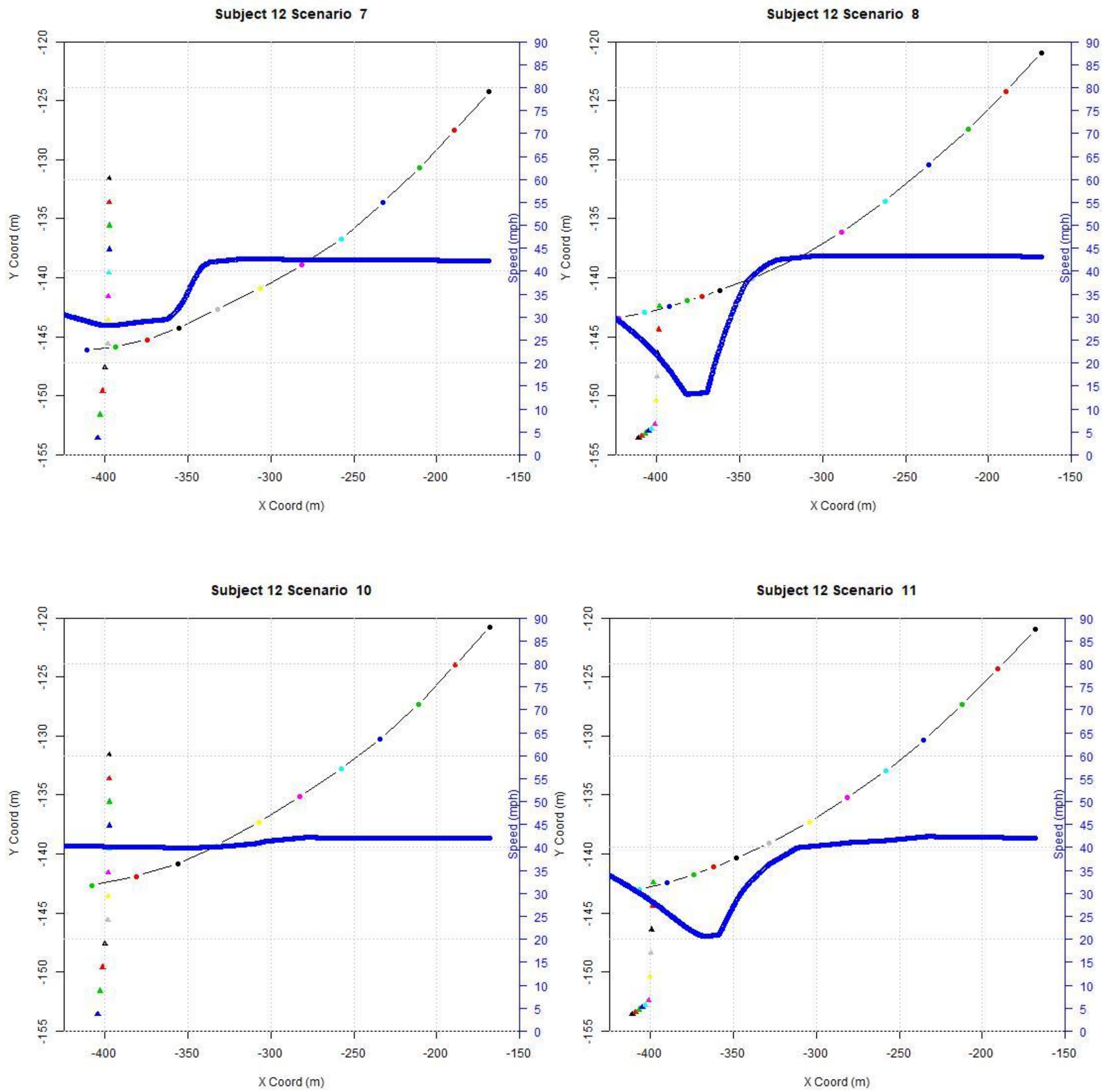


Figure E. 12 - Position and speed profiles of Subject 12

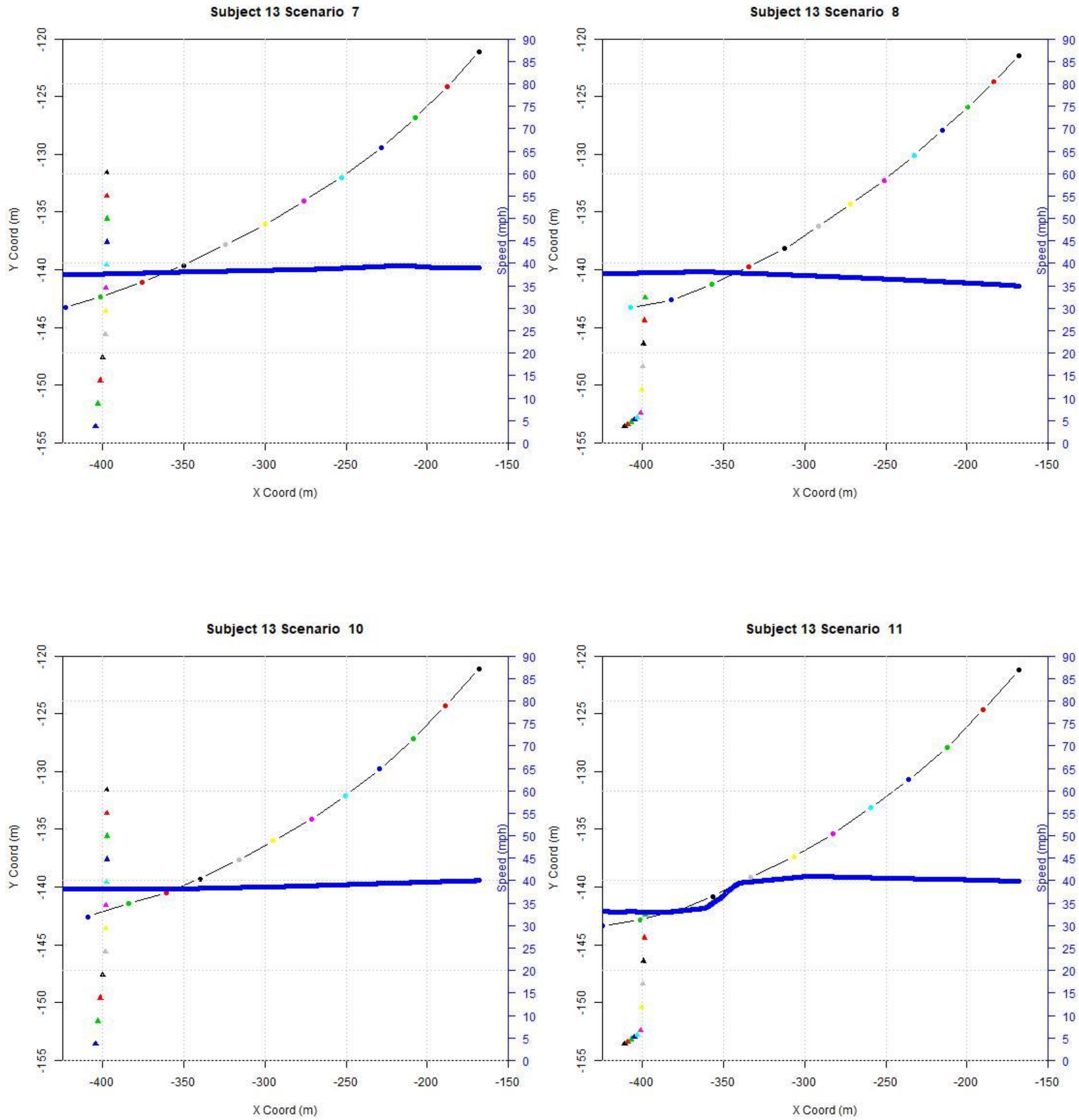


Figure E. 13 - Position and speed profiles of Subject 13

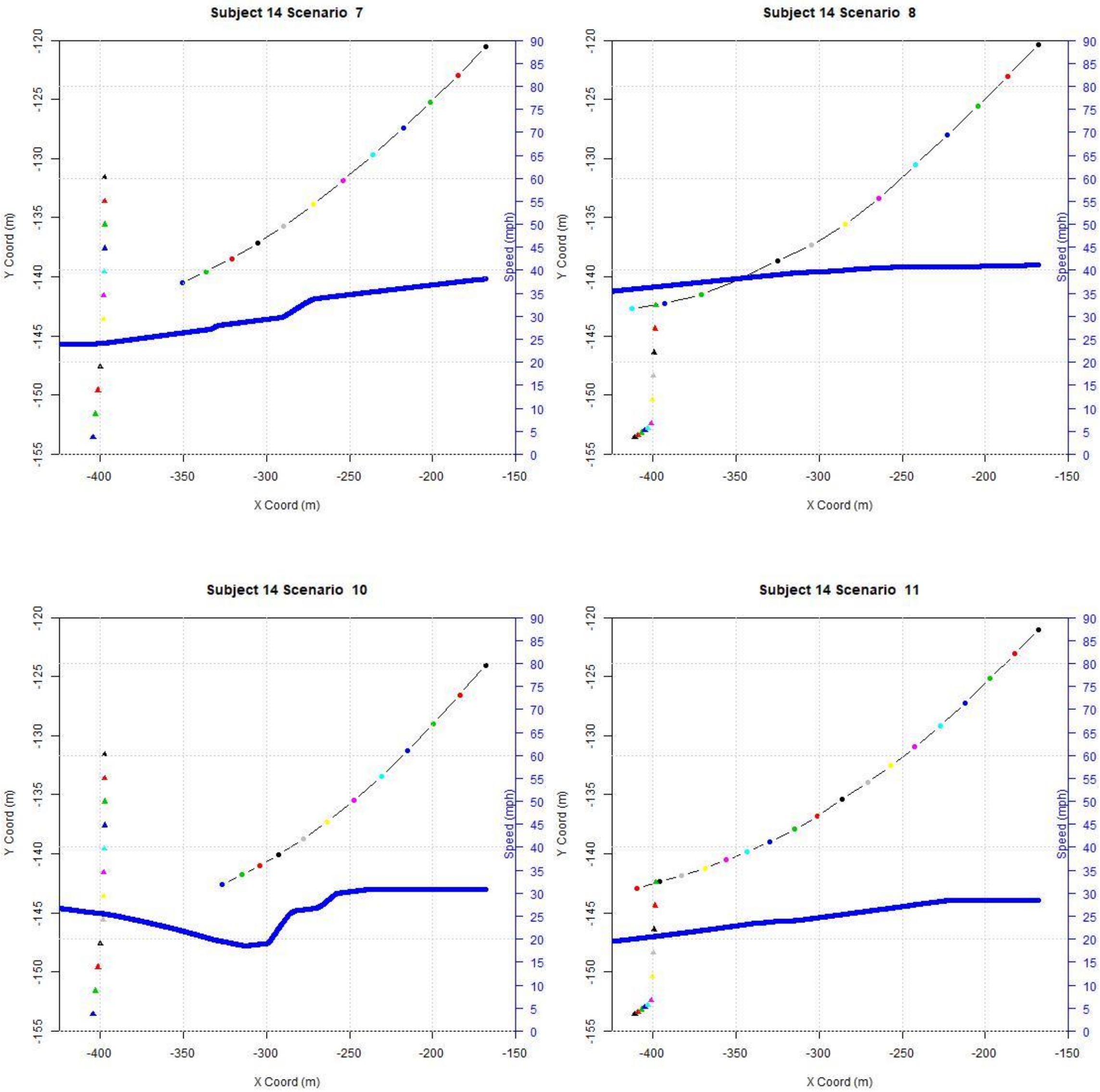


Figure E. 14 - Position and speed profiles of Subject 14

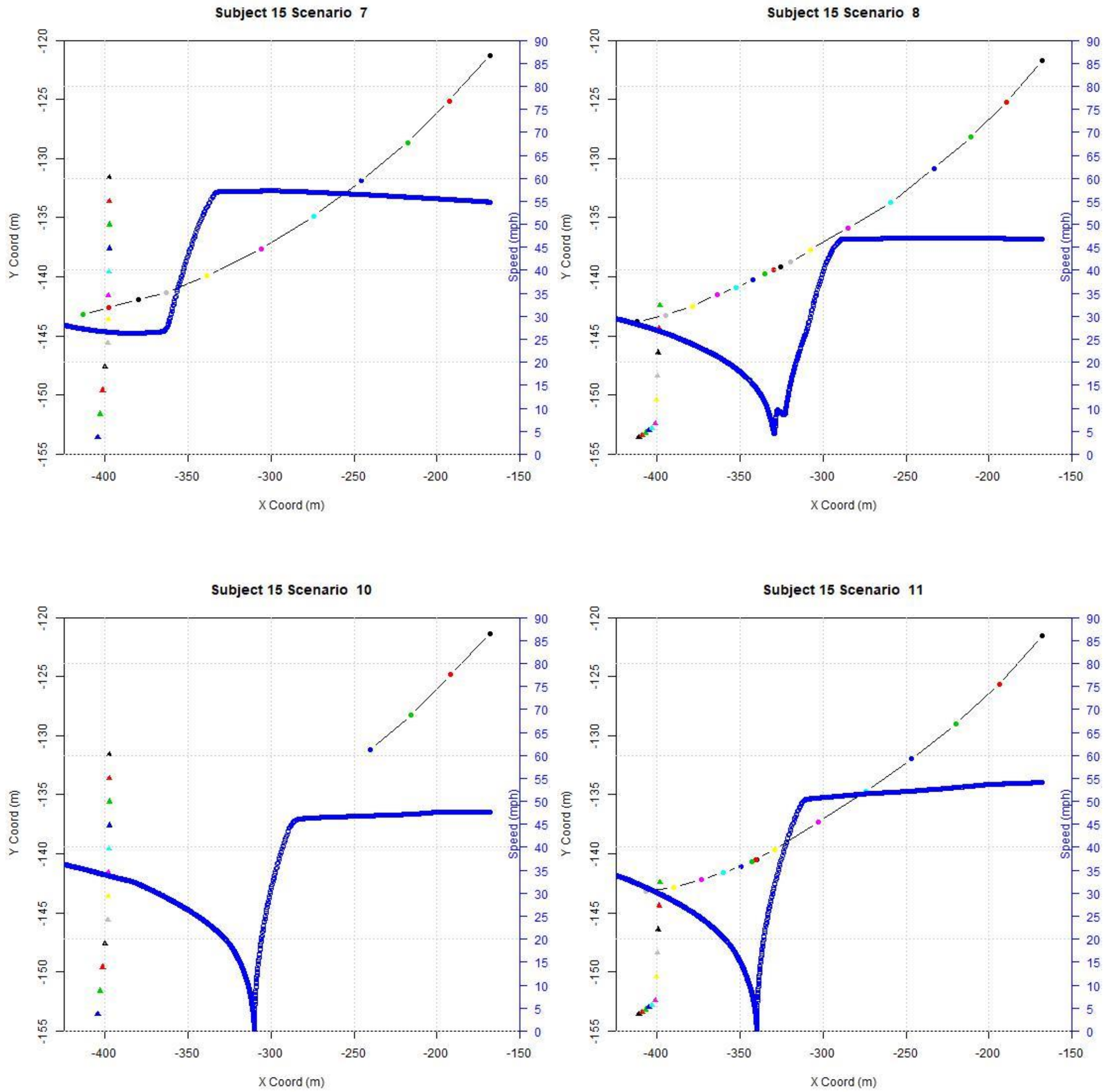


Figure E. 15 - Position and speed profiles of Subject 15

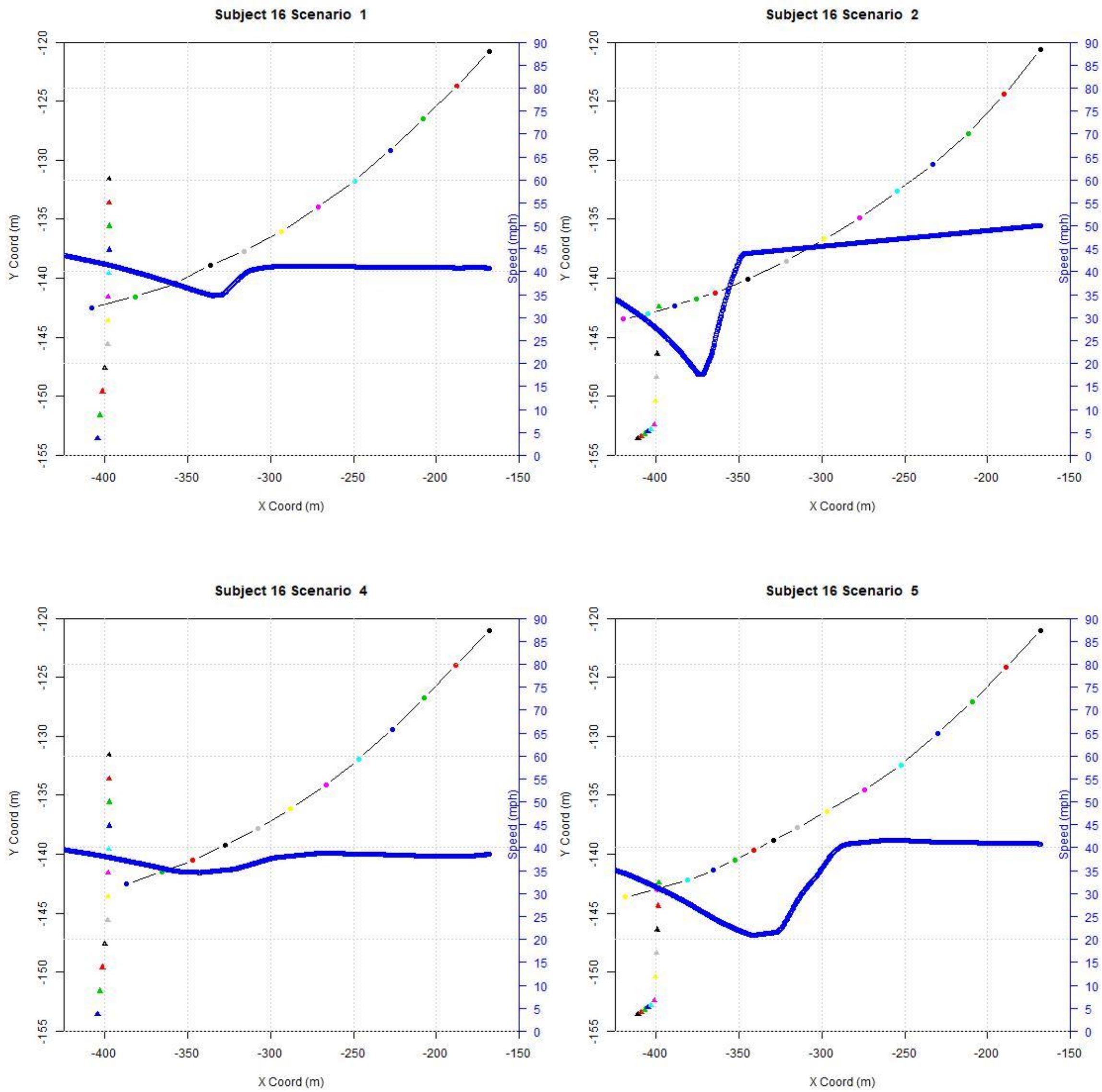


Figure E. 16 - Position and speed profiles of Subject 16

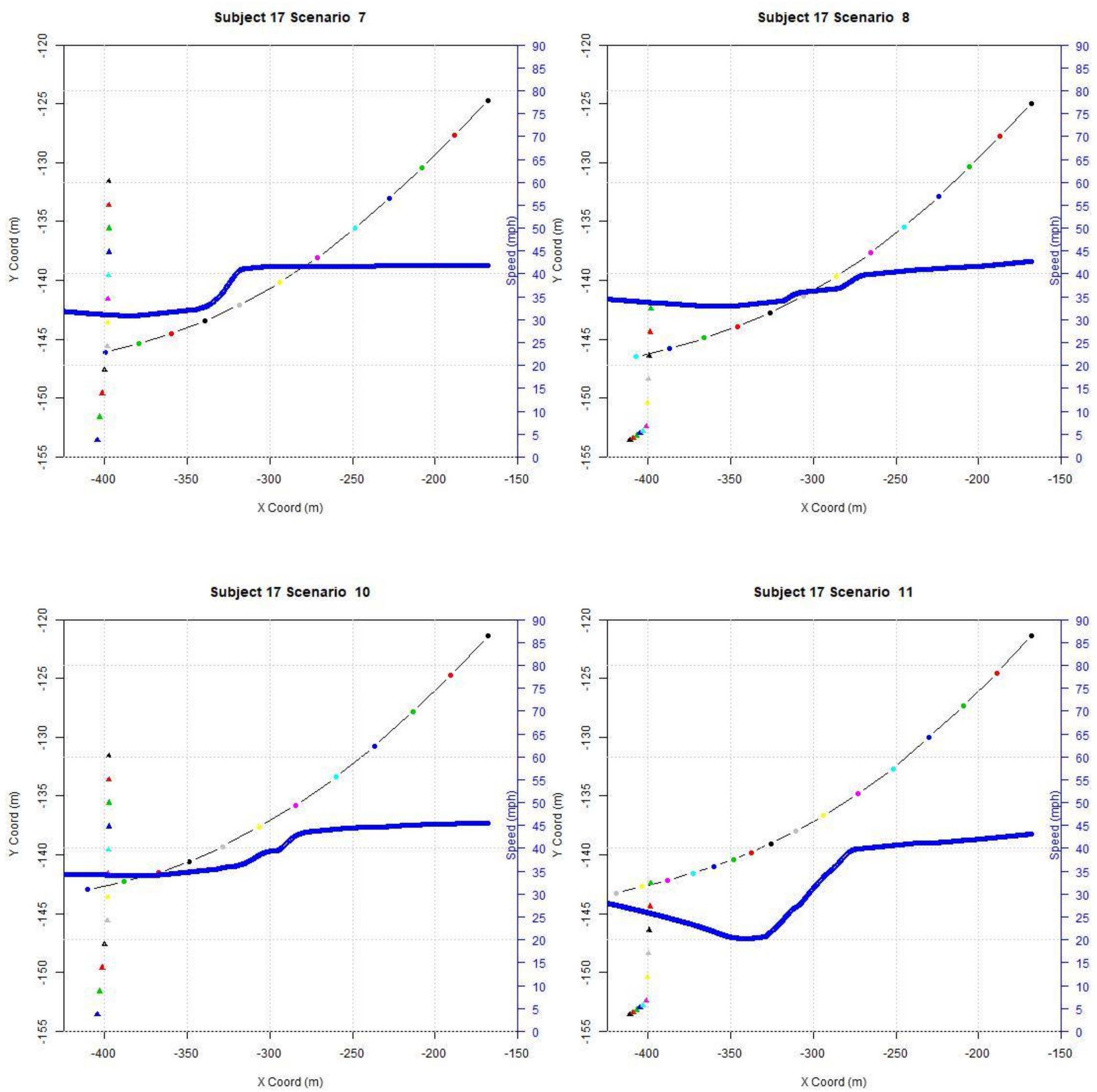


Figure E. 17 - Position and speed profiles of Subject 17

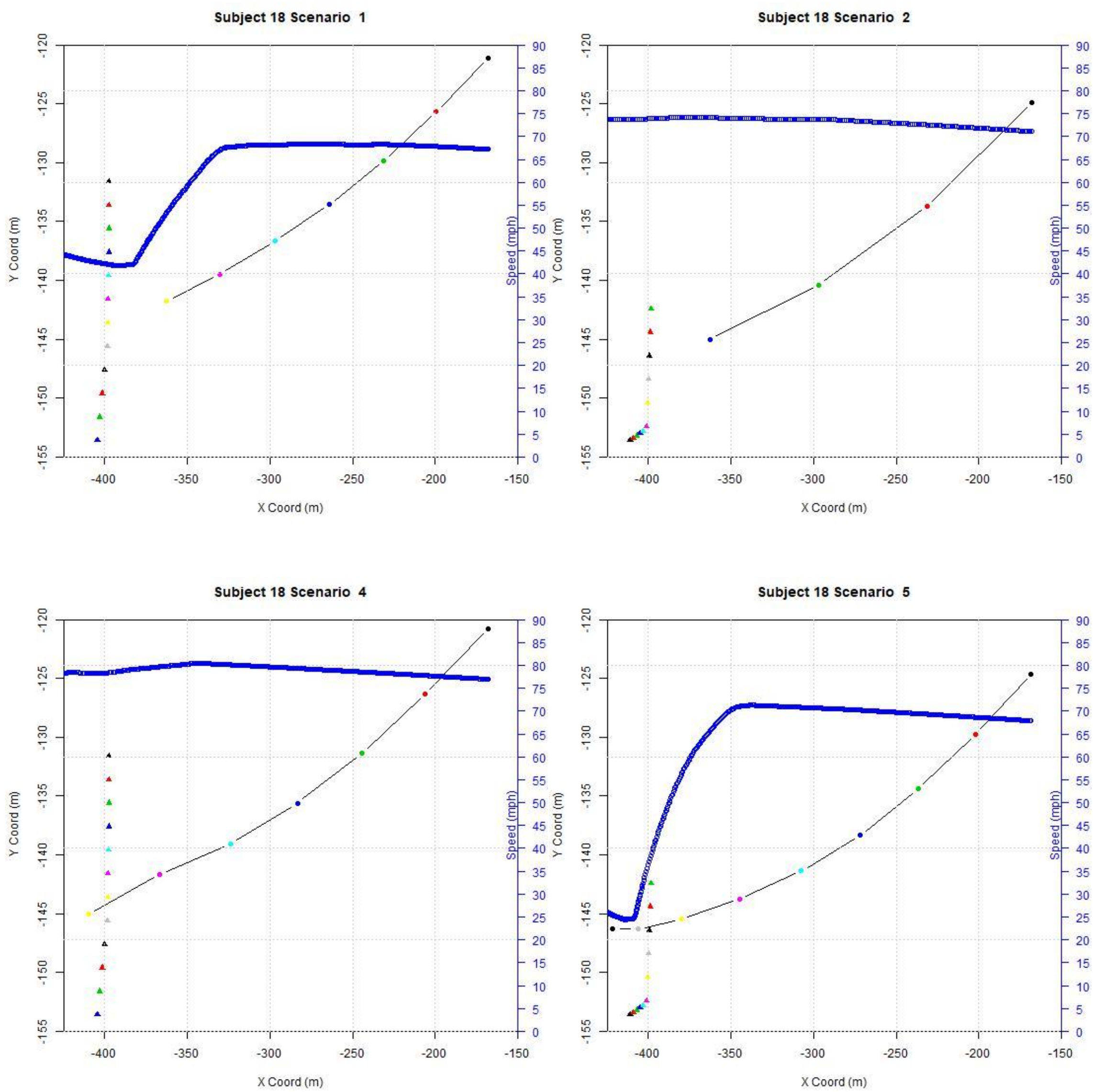


Figure E. 18 - Position and speed profiles of Subject 18

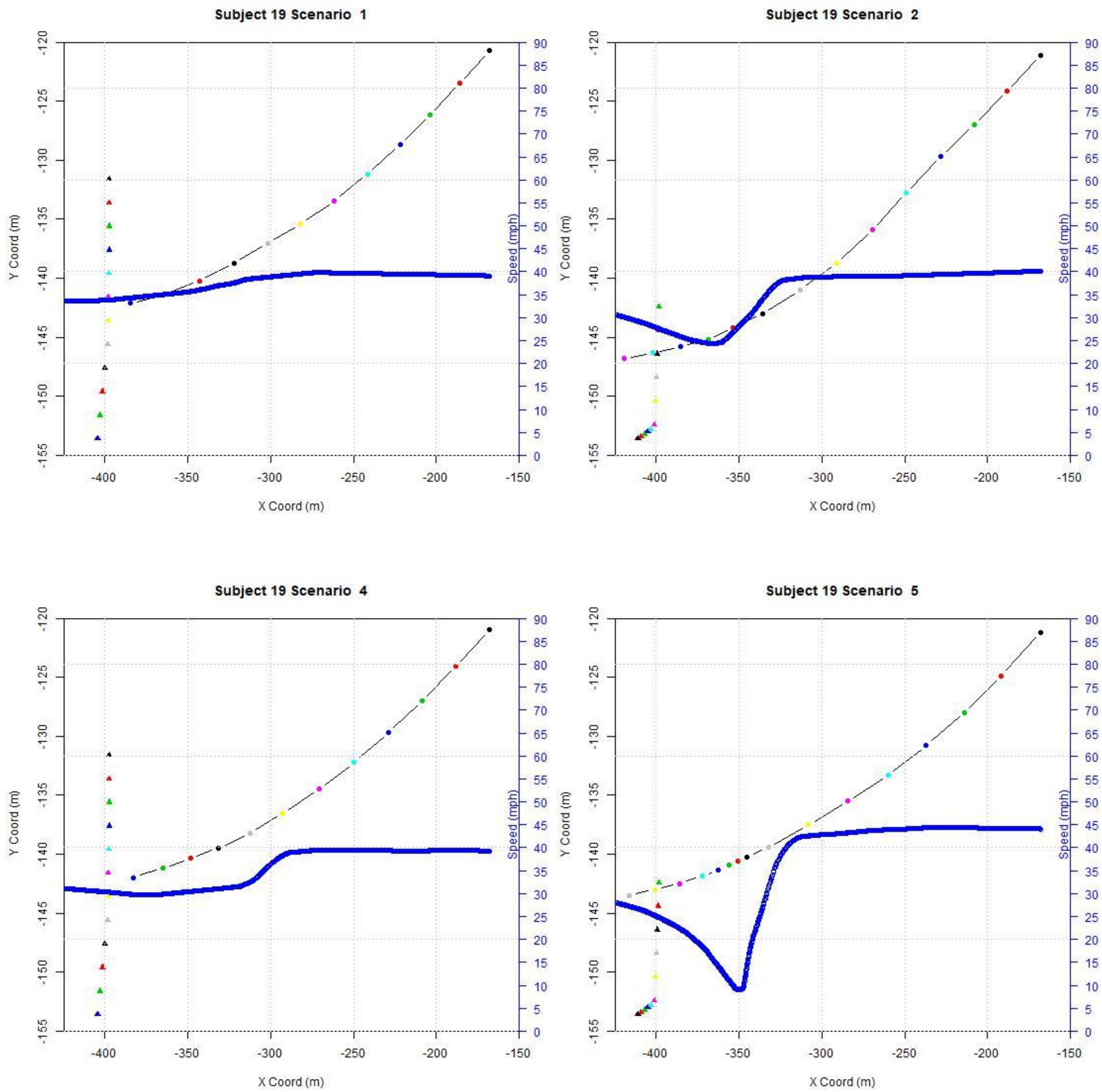


Figure E. 19 - Position and speed profiles of Subject 19

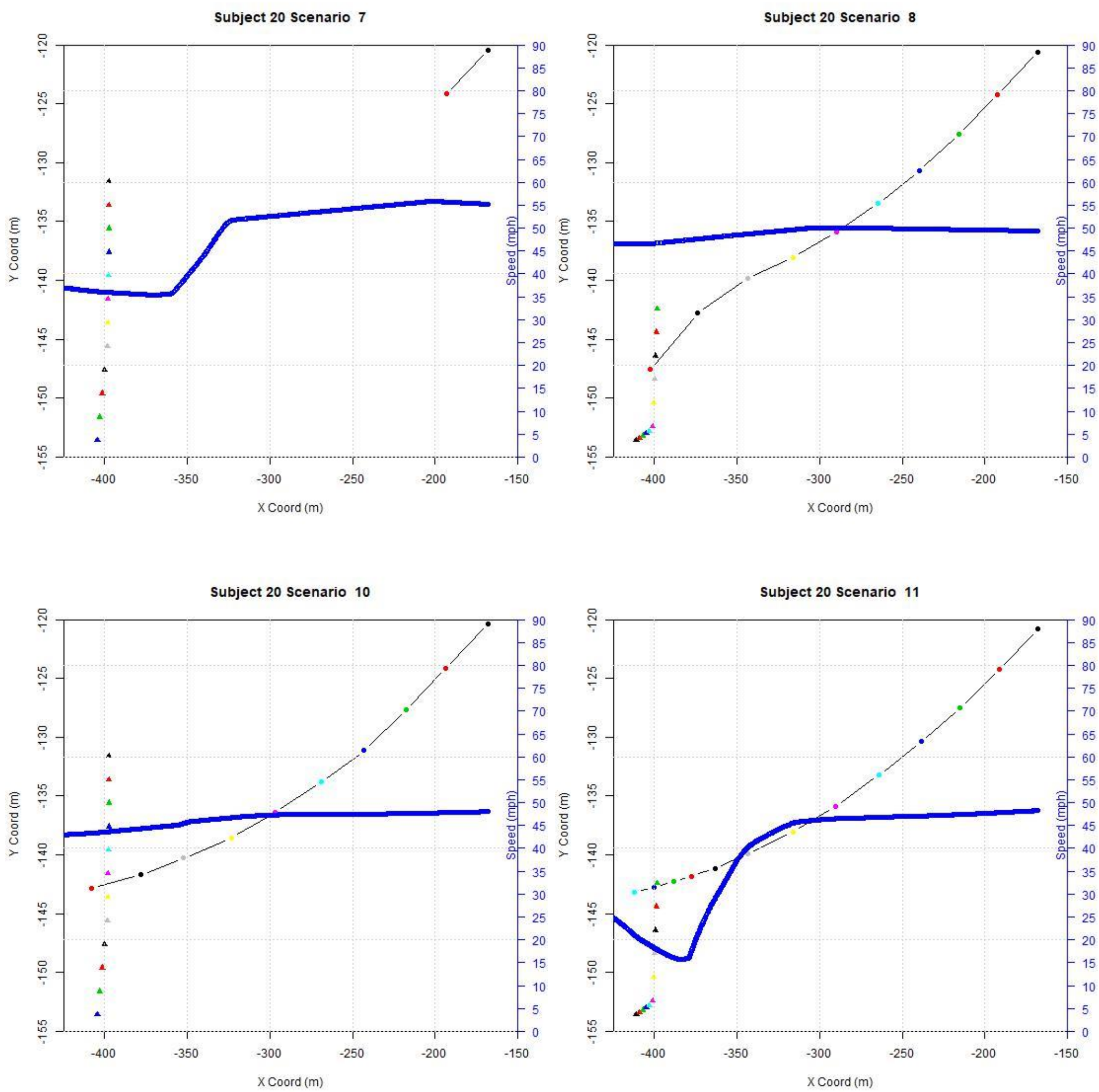


Figure E. 20 - Position and speed profiles of Subject 20

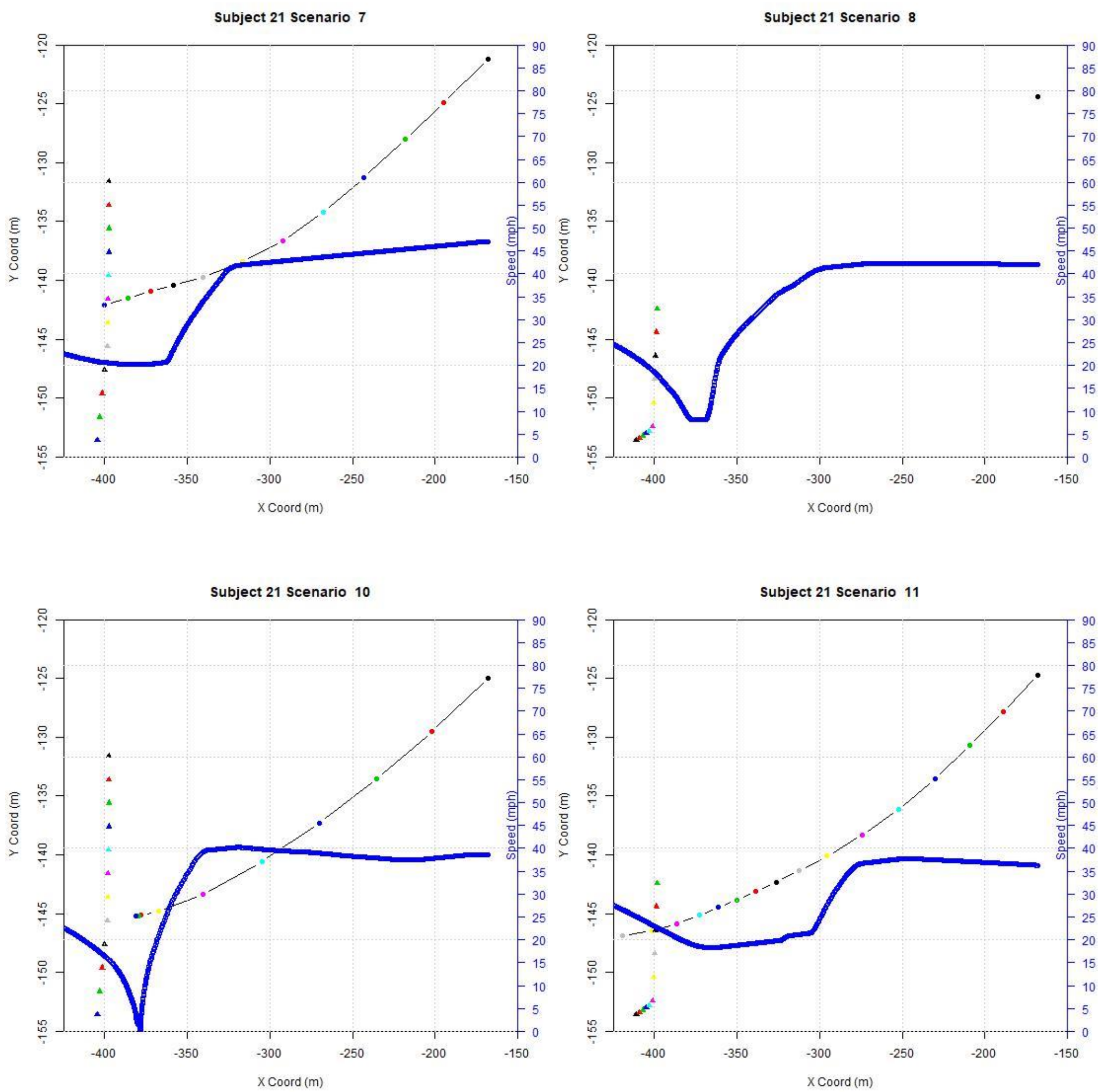


Figure E. 21 - Position and speed profiles of Subject 21

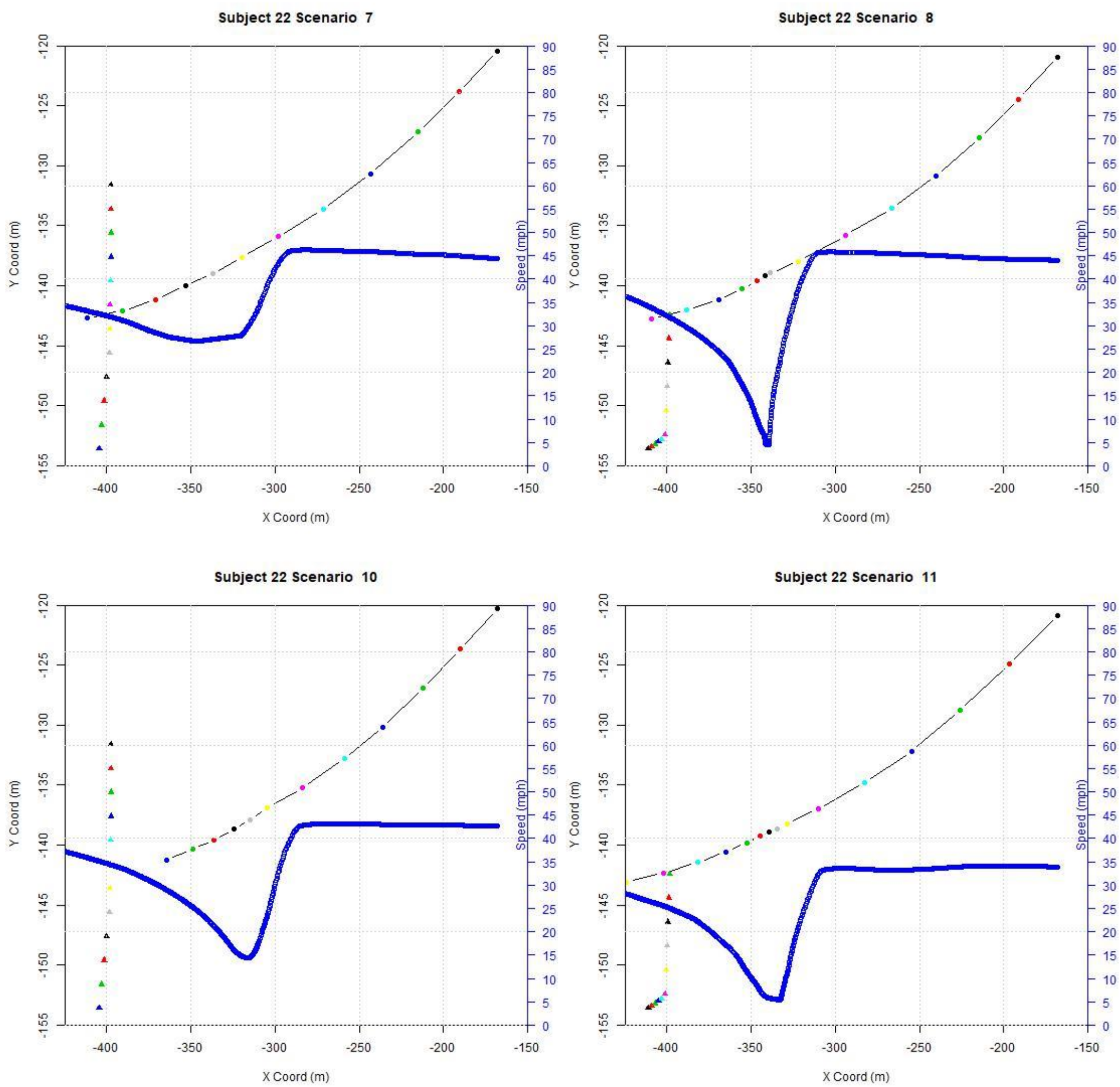


Figure E. 22 - Position and speed profiles of Subject 22

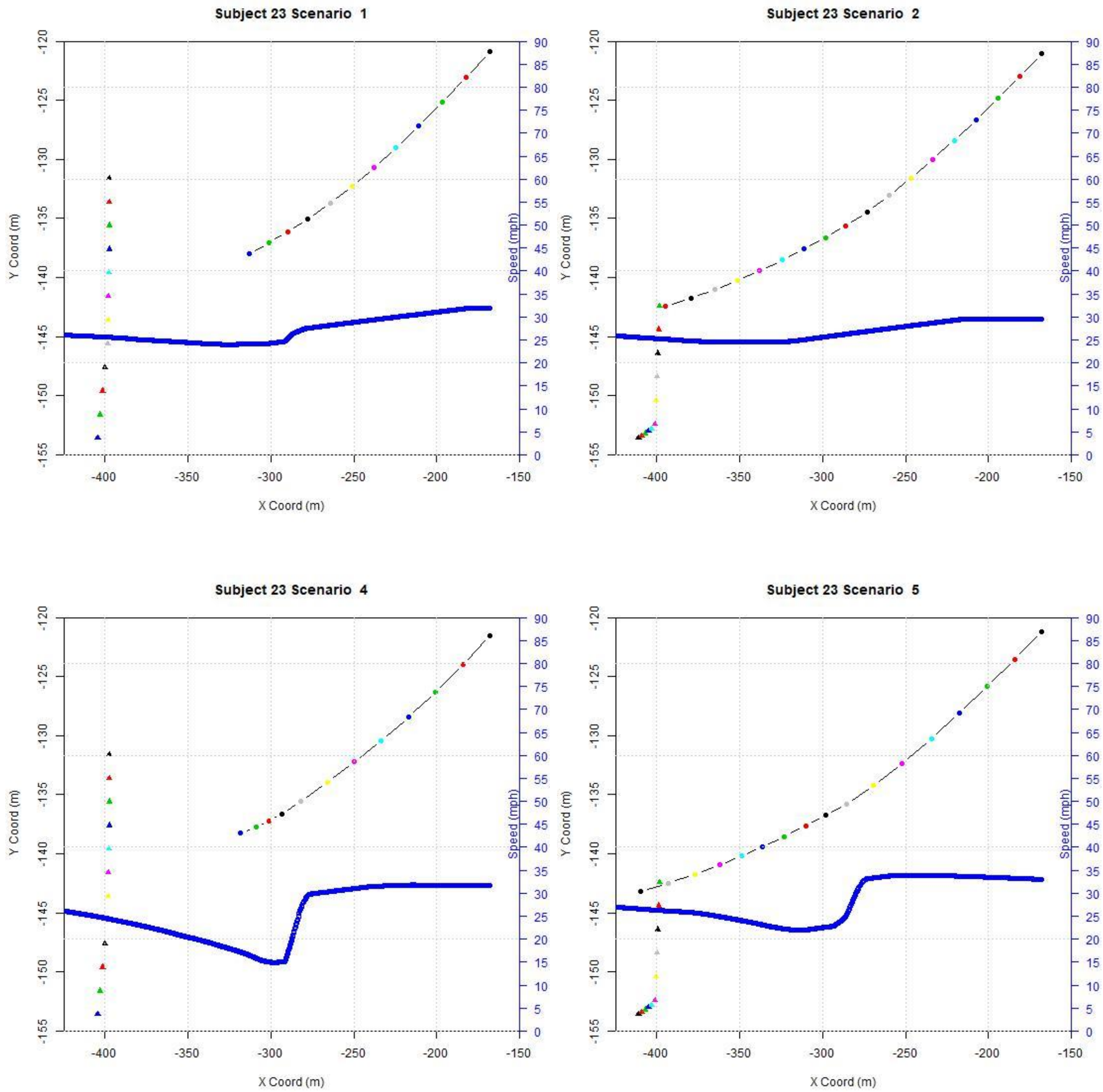


Figure E. 23 - Position and speed profiles of Subject 23

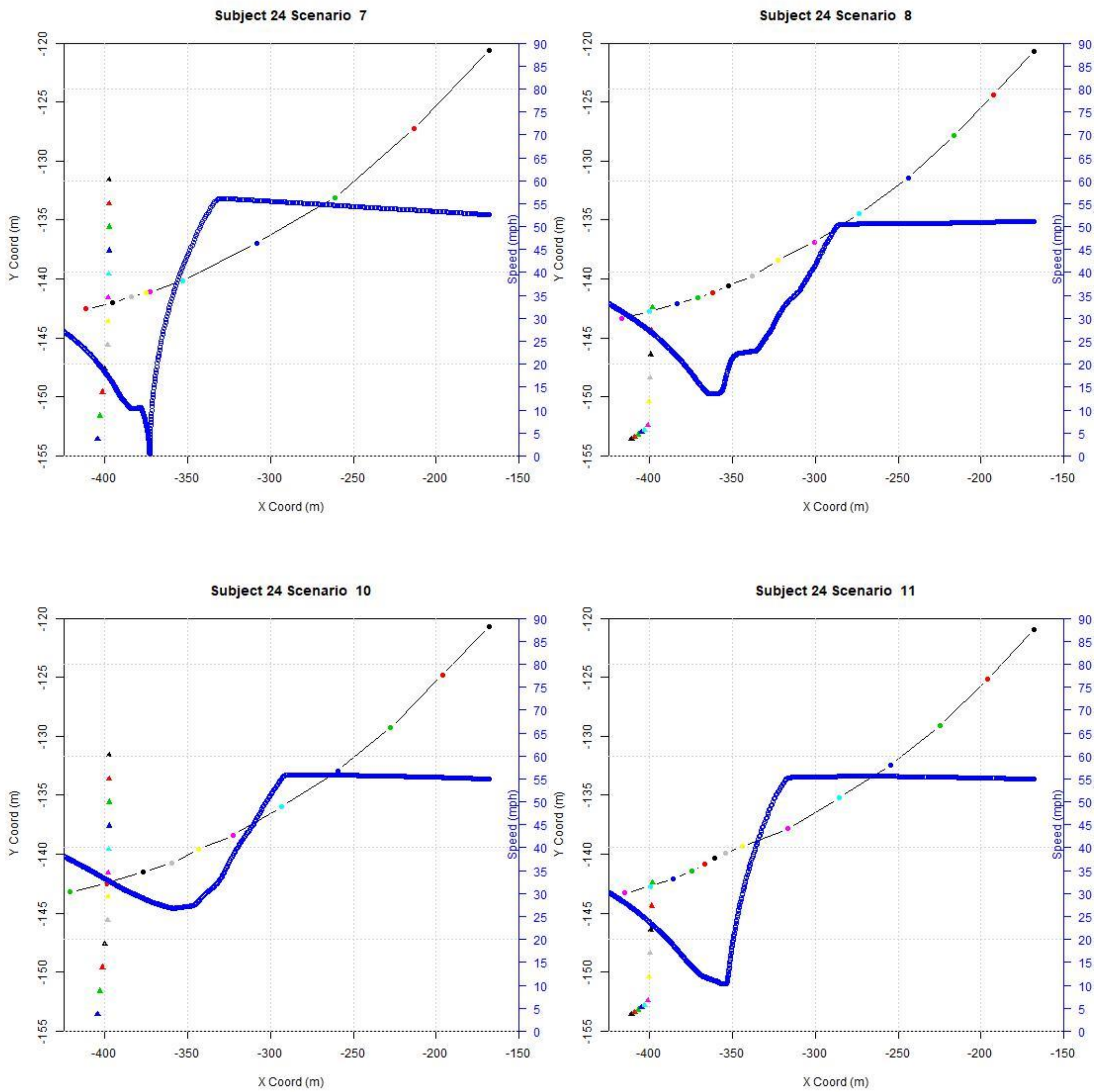


Figure E. 24 - Position and speed profiles of Subject 24

Appendix F: Franklin D. Roosevelt Speed

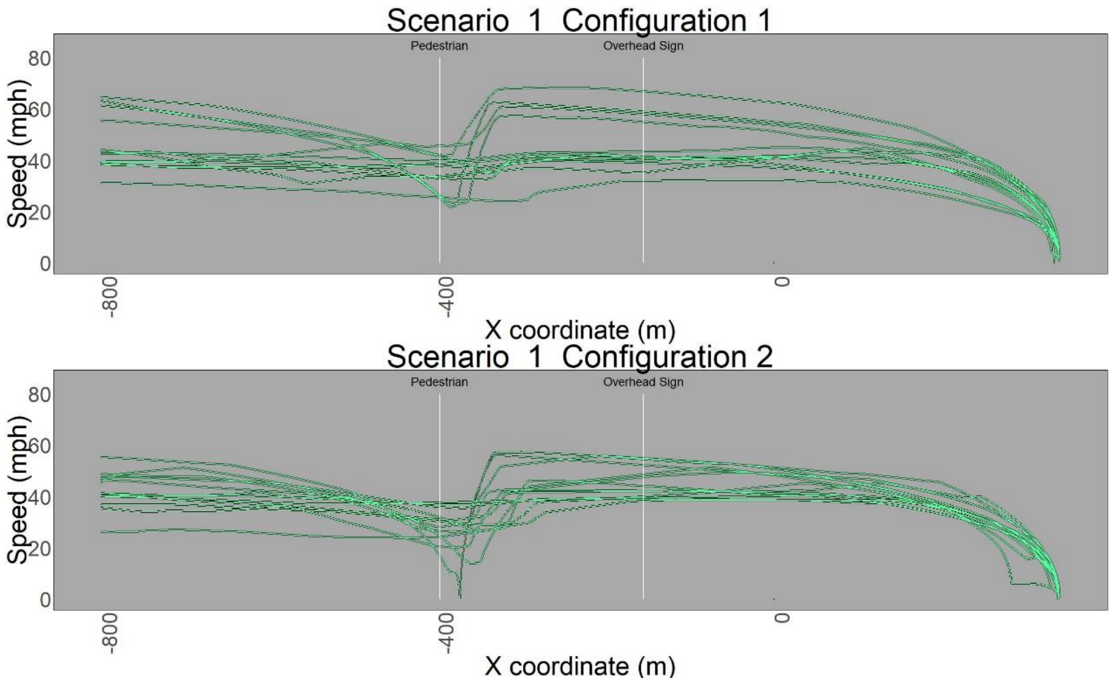


Figure F. 1 - Scenario 1 subjects' speed by configuration

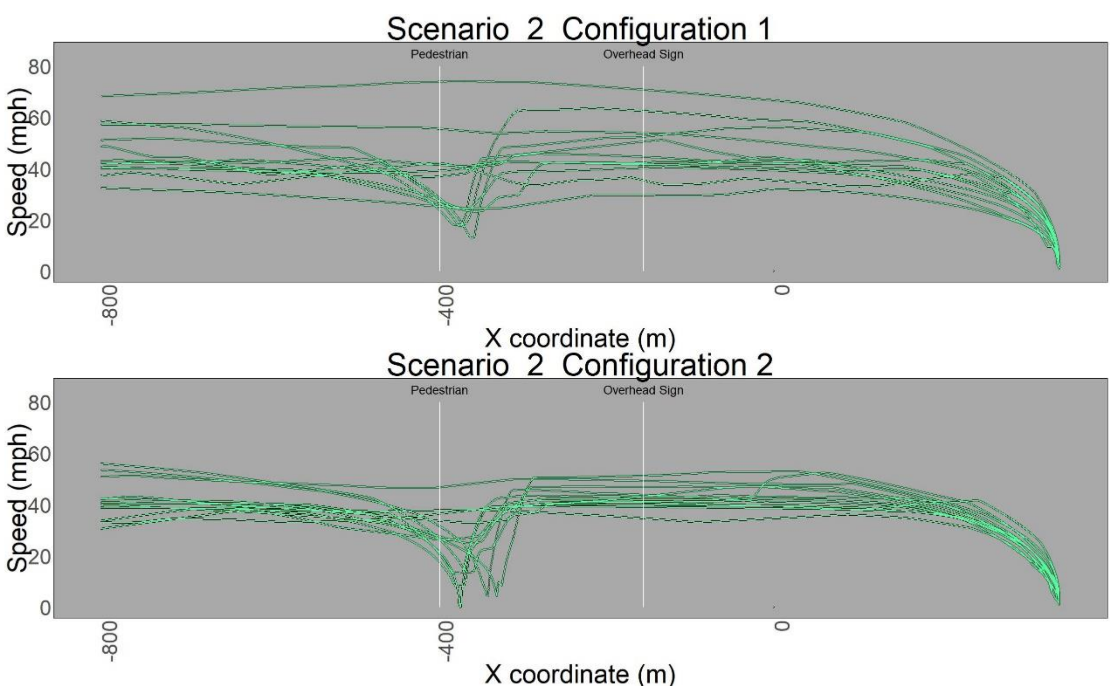


Figure F. 2 - Scenario 2 subjects' speed by configuration

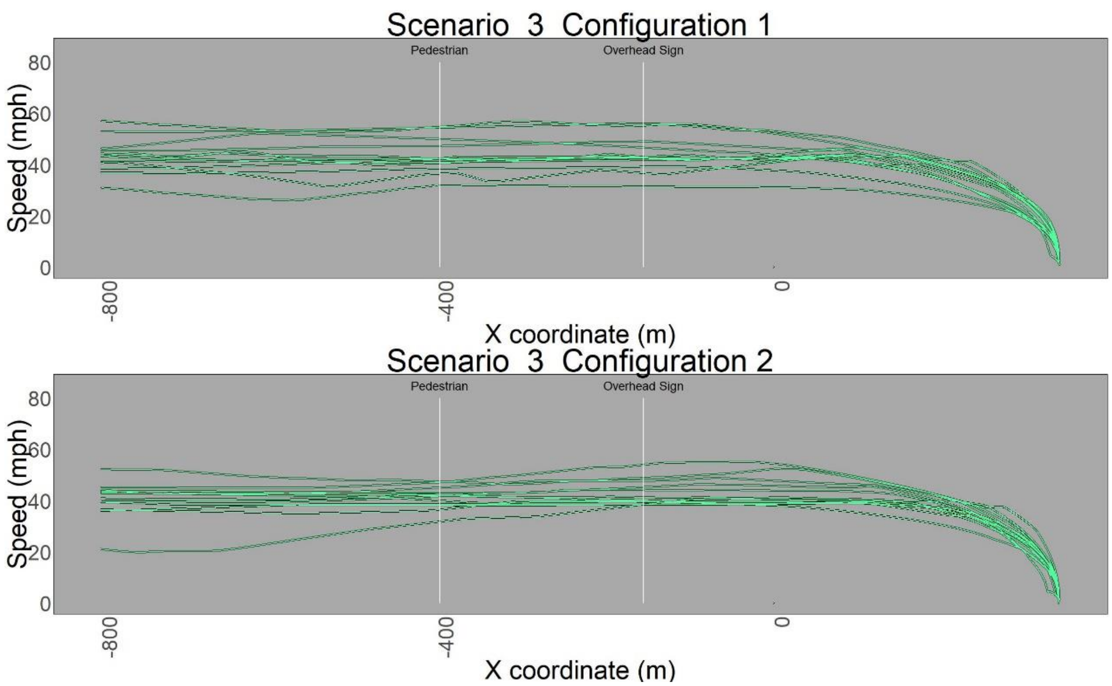


Figure F. 3 - Scenario 3 subjects' speed by configuration

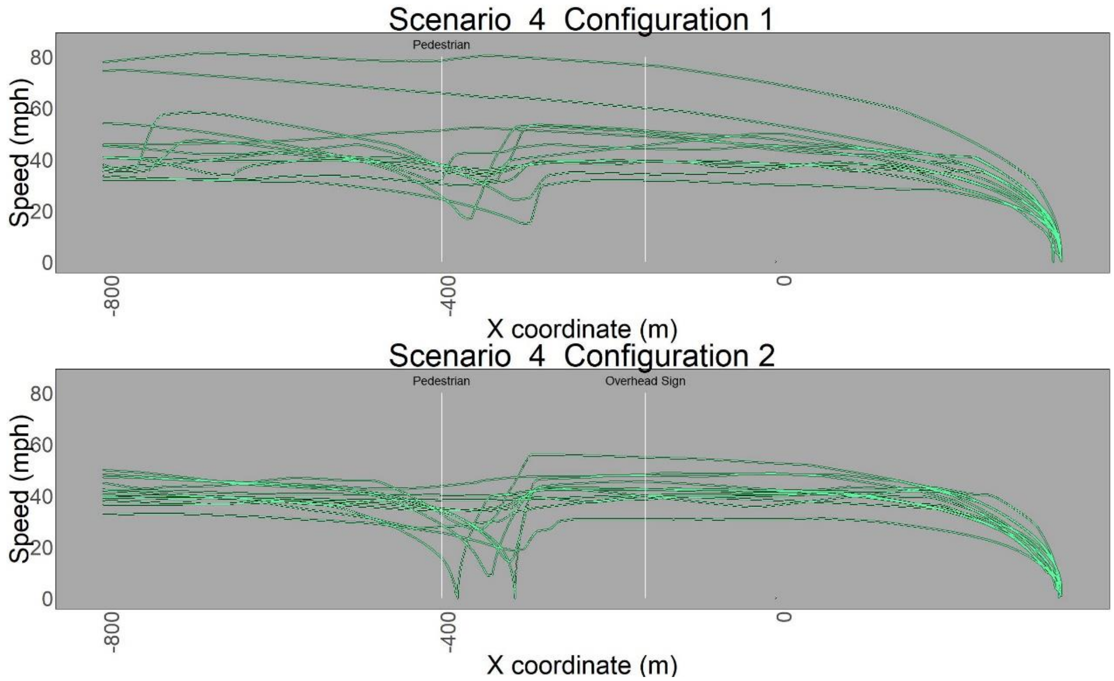


Figure F. 4 - Scenario 4 subjects' speed by configuration

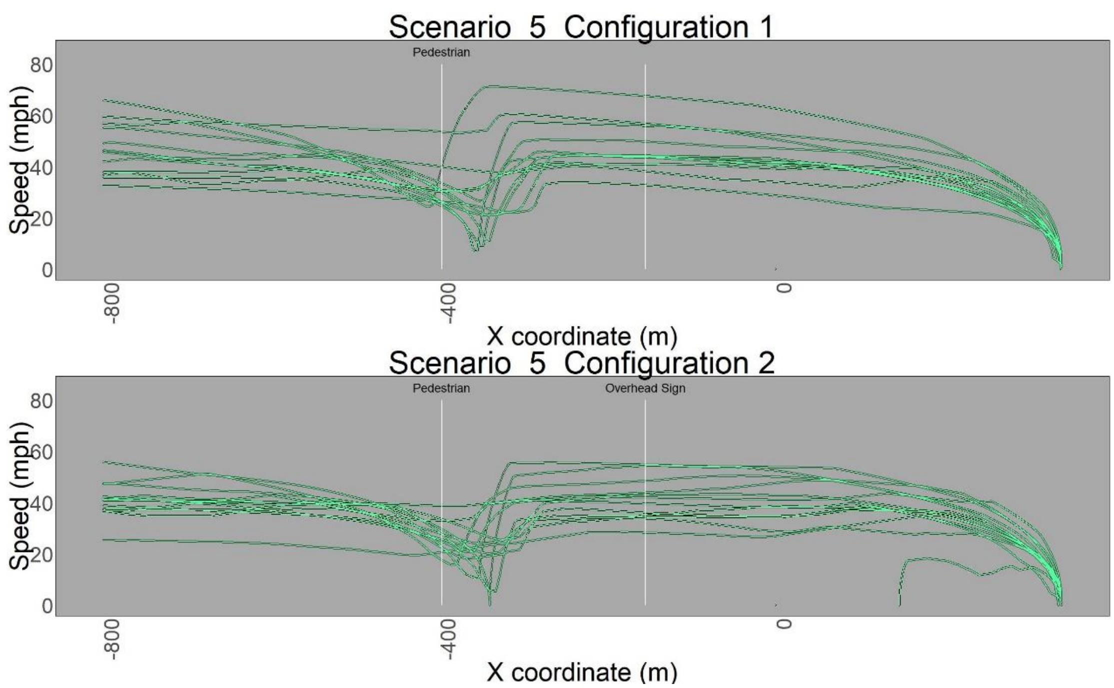


Figure F. 5 - Scenario 5 subjects' speed by configuration

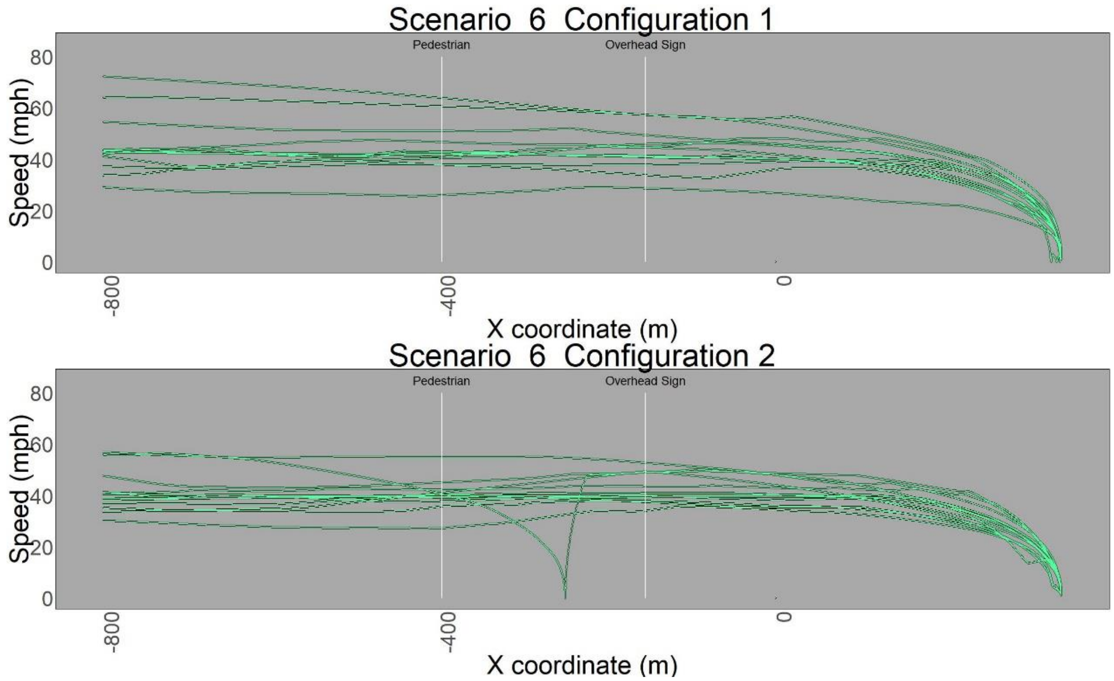


Figure F. 6 - Scenario 6 subjects' speed by configuration