

# Using Naturalistic Data to Develop Simulator Scenarios



**SAFETY RESEARCH USING SIMULATION**

**UNIVERSITY TRANSPORTATION CENTER**

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## Abstract

The establishment of large naturalistic driver data sets, most recently the Strategic Highway Research Program 2 (SHRP2), provides unique opportunities to observe driver behavior under real-world conditions. In order to better understand the relationship between simulation and naturalistic driving, it is becoming increasingly important to develop simulator scenarios with high ecological validity. Such scenarios may then be used to draw causal inferences regarding phenomena observed in naturalistic driving video. The goal of this project was to develop driving simulator scenarios from real roadways, specifically rural curves, where naturalistic data were collected as part of the SHRP2 research program. Once the scenarios were developed, data were collected on two driving simulator platforms, the National Advanced Driving Simulator (NADS) and the full-scale driving simulator at the University of Wisconsin – Madison, which runs on the Real Time Technology platform.

This report describes the process for developing the simulator scenarios from real-world data, the data collection and analysis process, and the implications for future research in transportation safety. Results from the experiments on both platforms are discussed, and they highlight the potential for a direct comparison between simulator data and naturalistic driving data. In addition to these promising results, this project will provide guidance on the future development of simulator scenarios from naturalistic data on multiple platforms, including challenges to be expected. The project results will provide an important step in bridging the naturalistic and simulator literatures.



## 1 Introduction

### 1.1 The Value of Driving Simulation

To understand the role of human behavior in crashes and crash avoidance, it is important to understand how drivers behave both in nominal everyday driving situations and in rare high-demand crash-avoidance scenarios. Transportation human factors research has historically taken a multifaceted approach to understanding driver behavior. These methods include naturalistic observations, test track evaluations, and driving simulator experiments. Each of these approaches has distinct advantages and limitations that must be considered to understand how drivers interact with vehicle technology. The goal of this project was to develop simulation using real-world data from a naturalistic driving study in order to merge the benefits of the two approaches.

Naturalistic data collection involves collecting observational data from cameras and other on-board sensors from drivers over an extended timeframe. These studies are particularly useful for understanding how drivers behave in everyday driving situations. For instance, recent naturalistic results provide insight into the frequency and type of driver interactions with secondary tasks (Victor et al., 2014).

The largest and most recent of these naturalistic studies is the Strategic Highway Research Program 2 (SHRP2). This data set contains data from over 3,000 drivers across six data collection sites, and comprises nearly fifty million vehicle miles traveled (Campbell, 2012). The accompanying Roadway Information Database contains roadway data from approximately 12,500 miles of road. The SHRP2 data contain a wealth of measures, including data from video recordings from inward- and outward-facing cameras and vehicle dynamics data such as speed and acceleration.

These large naturalistic data sets allow for unique insight into driver behavior. For example, the first round of research reports utilizing the SHRP2 data set (the SO8 reports) examined topics such as the role of distraction and visual behavior in traffic

crashes and lane departures on rural roads (Victor et al., 2014; Hallmark et al., 2013). By merging crash and near-crash (i.e., safety-critical) events across drivers, naturalistic studies can identify associations between different drivers, vehicles, and situational features and unsafe driving events. Importantly, the external validity of naturalistic studies is high given that behavior is recorded in drivers' own vehicle over an extended period of real everyday driving.

While the observational nature of naturalistic studies provides confidence in the generalizability of results, naturalistic studies are unable to draw causal relationships amongst variables of interest. Naturalistic driving essentially provides a snapshot of a single unique safety-critical event. Although much information can be derived from such analyses, it is impossible to isolate the specific causes of a safety-critical event. Furthermore, because crashes are rare and unique events, it is difficult to generalize results across situations and unsafe to recreate similar conditions in a test-track environment where the situation can be experimentally manipulated. While naturalistic data provide a glimpse into actual on-road behavior, such data sets are limited by the fact that they lack experimental control. Naturalistic data thus provide only a single snapshot into a driver's behavior at a single moment in time under specific conditions. Factors that might influence behavior, such as distraction or roadway conditions, are not experimentally manipulated, and it is therefore impossible to draw causal conclusions.

Driving simulation can address some of these limitations. By utilizing an experimental approach, it is possible to isolate causal mechanisms behind crash events and driver performance errors. Simulation has been a fruitful tool for studying topics such as driver distraction (Fisher et al., 2011), cognitive aging (Freund et al., 2002), and driver-vehicle interface design (Wang et al., 2010). The benefit of driving simulation is that these factors can be manipulated repeatedly and experimentally in a safe and controlled environment. High-fidelity simulators, such as the NADS-1 at the University of Iowa (UI), also provide high levels of immersion and precise motion feedback.

Ideally, simulator studies could be utilized in concert with naturalistic observations to address the range of research questions in human factors transportation. This relies on the assumption that simulator results will translate to real-world driving situations. Previous research suggests a fairly high level of validity for driving simulators in studying topics such as distraction and vehicle control (e.g., Wang et al., 2010). However, a problem arises when simulator results fail to match the patterns of behavior observed in naturalistic studies. Recently, for instance, discrepancies have been shown between simulator and naturalistic results relating to cognitive distraction. Considerable simulator research shows the detrimental effects of conversing on driving performance (e.g., Horrey & Wickens, 2006). Recent naturalistic data, however, show limited costs to conversation alone (Victor et al., 2014). If simulation is to be a useful tool in informing safety and policy decisions, it is critical that simulator scenarios replicate the conditions and features of real, on-road driving. Simulator scenarios inherently lack at least some of the complexity found in real driving. Furthermore, the tasks performed in simulator drives are often considerably simplified versions of on-road tasks (e.g., car following paradigms). This raises concerns about the validity of simulation for generalization to on-road behavior.

To that end, the goal of the present project was to develop and validate simulator scenarios based on naturalistic driving data. As part of an ongoing SAFER-Sim project, a collaborative team from the UI and the University of Wisconsin (UW) developed a method for translating real-world road data into simulator scenarios. The current proposed project leveraged this approach to develop simulator tiles from the SHRP2 naturalistic data set.

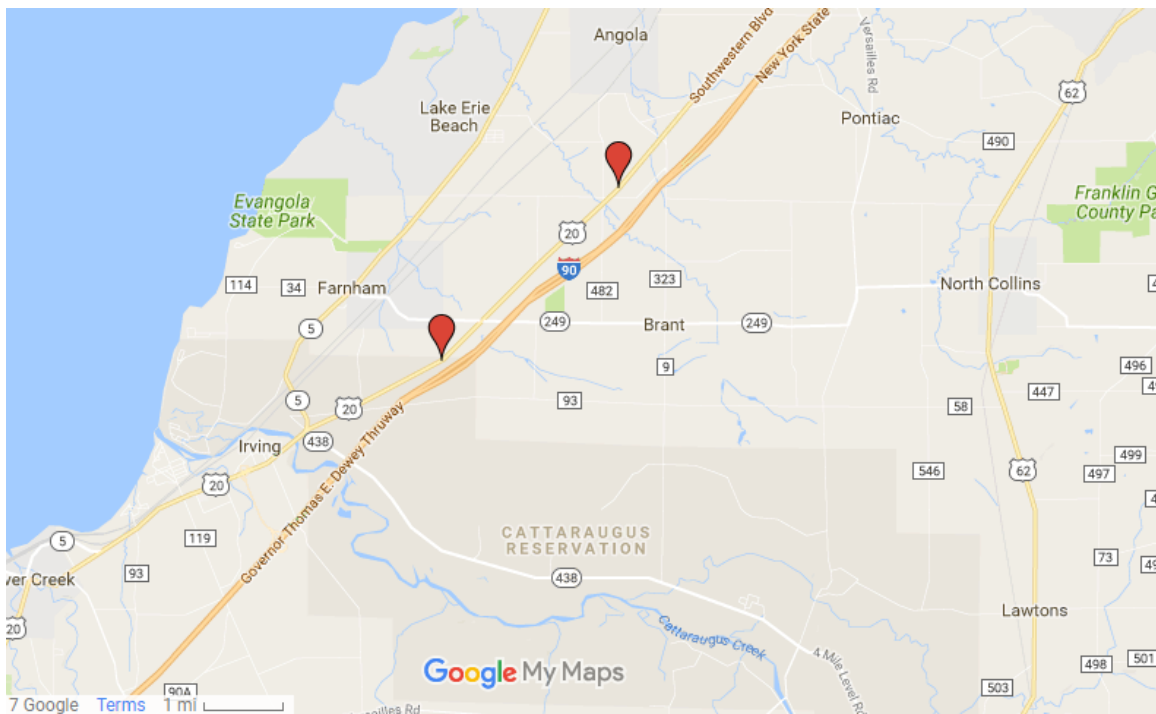
## 1.2 Study Objectives

The goals of this project were twofold. First, we implemented and refined a process for creating driving simulator environments based on real-world data. Second, using the

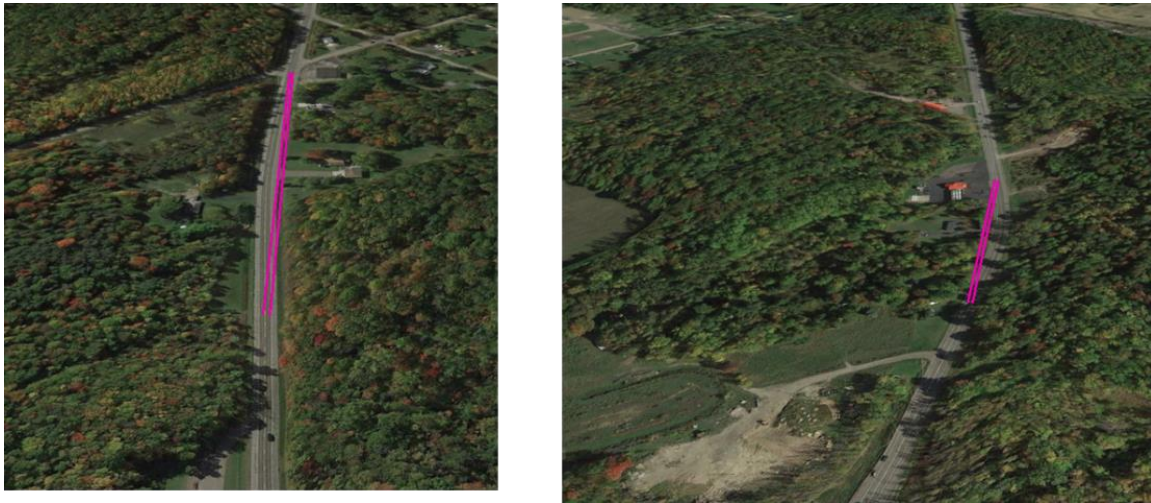
ensuing simulator tiles, data were collected from a sample of research participants in two driving simulators of varying fidelity under different driving conditions.

## 2 Simulator Tile Development

The first step in the development of the simulator tiles from naturalistic data was to identify sections of roadway to recreate. When this project began, the first round of reports using SHRP2 data had been completed (i.e., the S08 Reports). One of these reports examined driver roadway departures across a range of rural curves. We decided to reproduce two of these curves using the simulator tile development approach described below. Selection of the curves was based on discussions with the Iowa State team that had recently conducted an analysis. The two selected curves, shown below in Figure 2.1 and Figure 2.2, were those with the highest number of trips by unique drivers in the SHRP2 data used for analysis in the S08 report (31 or more trips across each curve, respectively).



**Figure 2.1 Location of the two SHRP2 rural curves**

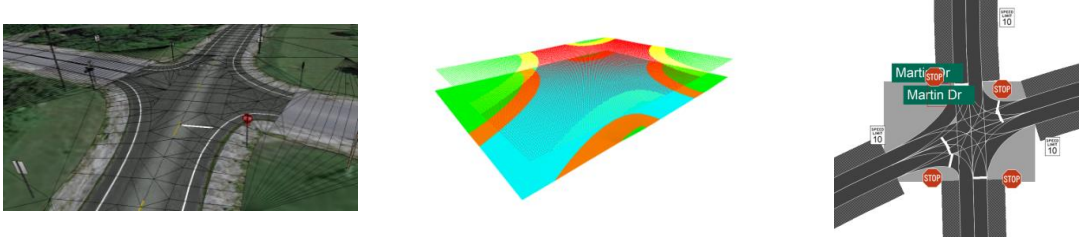


**Figure 2.2 Google Earth views of curves selected for simulator development**

The National Advanced Driving Simulator (NADS) simulation architecture relies on attributes to describe and define the physical characteristics of roadways, junctions, and objects in the production of a simulated world. There are two categories of data: the visual model, which consists of everything visible within the simulator, and the virtual model, which describes key elements of the visual model within a correlated virtual environment model (CVED; see Figure 2.3). The CVED attributes of the world include road and lane definitions, road type, surface material and default speed limits, road network lane connectivity, drivable terrain data and objects such as traffic signals and signs, as well as intersection hold offsets. These objects and their attributes are used by the simulation software to permit autonomous vehicles to navigate the world while obeying common traffic performance metrics such as following the speed limit for any given road, establishing right-of-way priority at intersections, and lane-change behavior.

The CVED attributes are developed in conjunction with or derived from the visual model to minimize mismatches between the visual and correlated virtual models. To facilitate development and production of simulator worlds, NADS relies on a library of component modules that include visual models, CVED virtual model data, and a global library of data referenced by each model. These models take the form of textured 3D

geometry and associated data files that are collectively referred to as tile models. Tile models must be developed following conventions that define model sizes, roads, junctions, and objects such as signs.



**Figure 2.3 Visual model, elevation map, CVED view of model (left to right)**

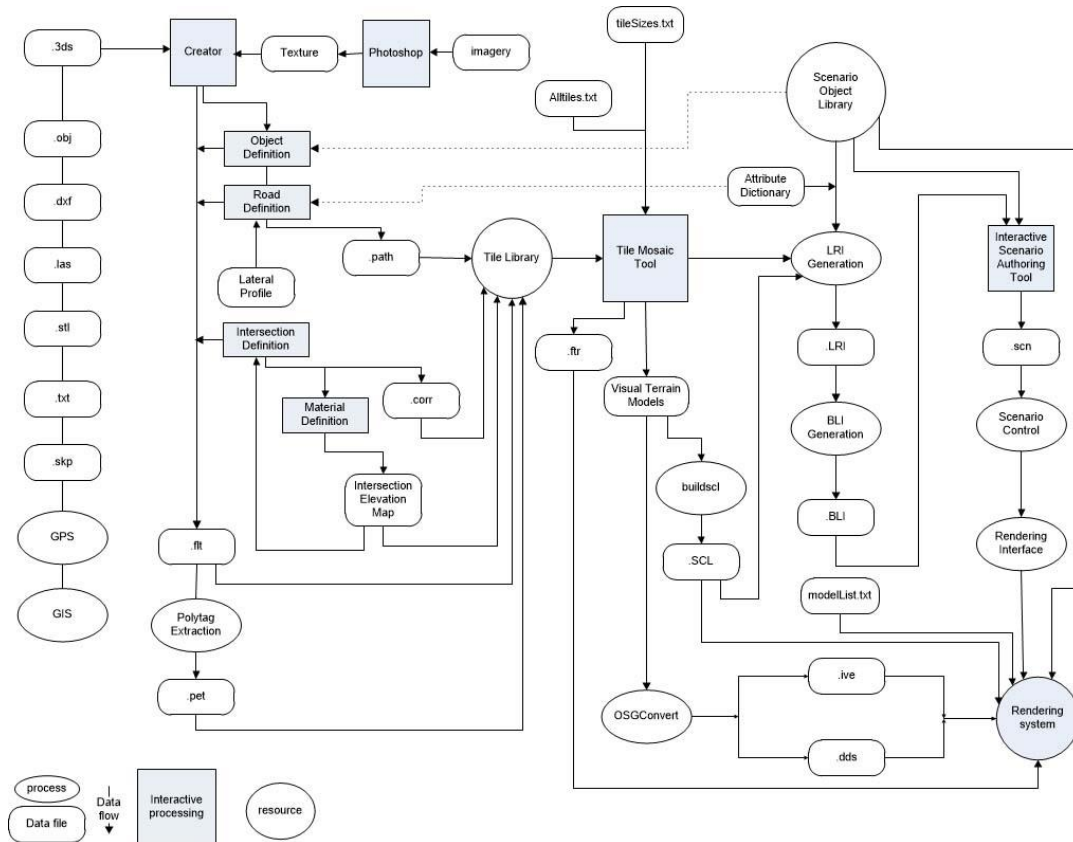
The following sections present the production methods associated with development of a tile model for the NADS simulators derived from SHRP2 data using various editors and data-processing programs.

### 2.1 Tile creation from SHRP2 data.

Developing a tile model roadway requires information about the road being developed, including road type, surface material, curve radius, and super-elevation. It is also helpful to know the general visual character of the roadway, such as new asphalt versus cracked and aging concrete. To include intersections on any road that is not flat also requires the creation of an intersection elevation map, which is a rectangular grid of elevation posts. Intersections also require the creation of lane connections, which are essentially special-purpose, one-way road paths that define the connection centerline between two road lanes.

This section describes the process of using Autodesk Civil3D to construct a roadway using SHRP2 data for road parameters such as roadway centerline, radius of curvature, and super-elevation. The construction process is manual and follows the design and construction methods typical for Civil3D, which is effectively a process of guided interactions between the designer and the software. Various design parameters are

presented to the user, and the end result is a simple roadway model with geometric surfaces and line elements. Civil3D maintains such data as internal database records that must be exported in order to be accessed and used from outside the Civil3D application. Automatically processing the design data and geometry requires mapping elements from the design domain in Civil3D into the simulation model domain.



**Figure 2.4 Data and process pipeline source to render**

The process of tile model creation is illustrated in Figure 2.4. The process begins with roadway data in one of many formats. Currently, most processing stages require manual user interaction or are semi-automated, from importing data or model geometry into Creator™ to adding object and road definitions and integrating tile model data into the Tile Library. Once integrated, new assets are available for use in the Tile Mosaic Tool and may be used with existing legacy assets to build new simulation worlds.

Publishing a world generates all files necessary for simulation except for scenarios (events built to occur within the simulated environment).

### 2.1.1 Generate roadway alignment using AutoDesk Civil3D

Alignments consist of the longitudinal road design and describe the overall form of the road as shown in Figure 2.5.

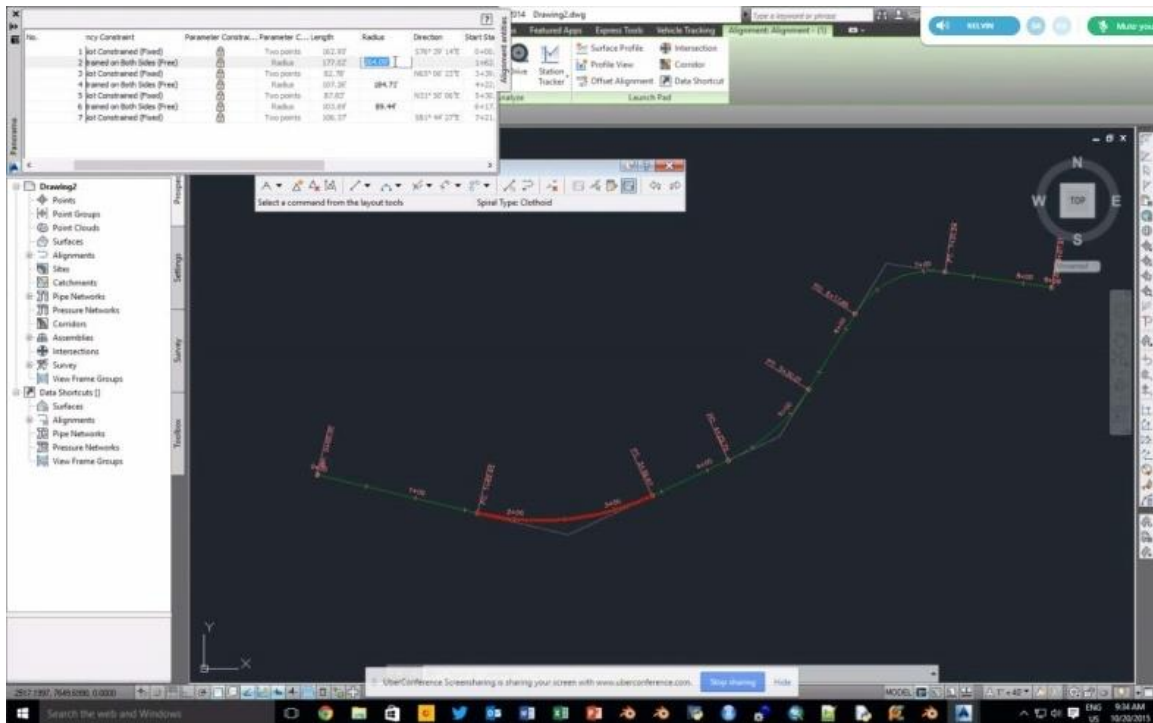


Figure 2.5 Civil3D road alignment

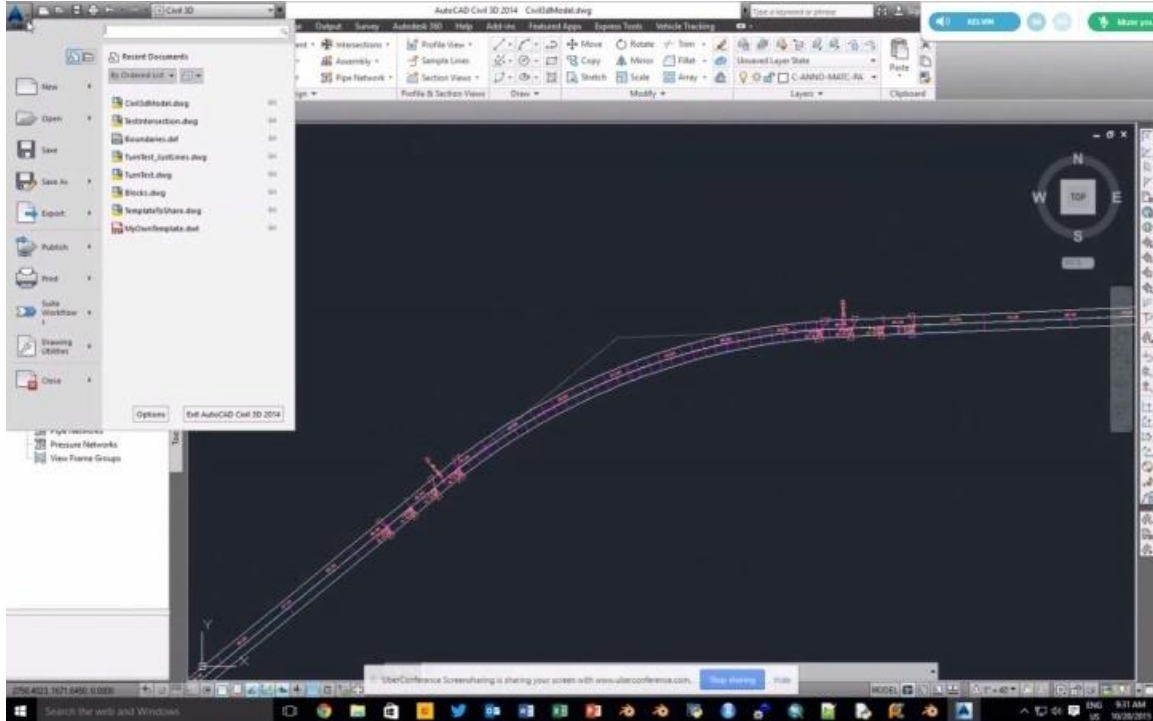
### 2.1.2 Use SHRP2 roadway data to define curve geometry

The initial alignment is edited to use the radius, curve length, and super-elevation data from the SHRP2 database. These parameters are entered manually into the alignment using standard design inputs within Civil3D and refine the road design as shown in Figure 2.6.

Once the parameters have been entered, the roadway is extended to comply with NADS tile model size and edge conventions. To satisfy tile model size and edge conventions, the roadway is extended to permit the roadway to exit the tile model centered on a 660-foot edge. Tile models are based on units of 660 feet, which ensures



that compatible models can be attached to each other within the world assembly application.



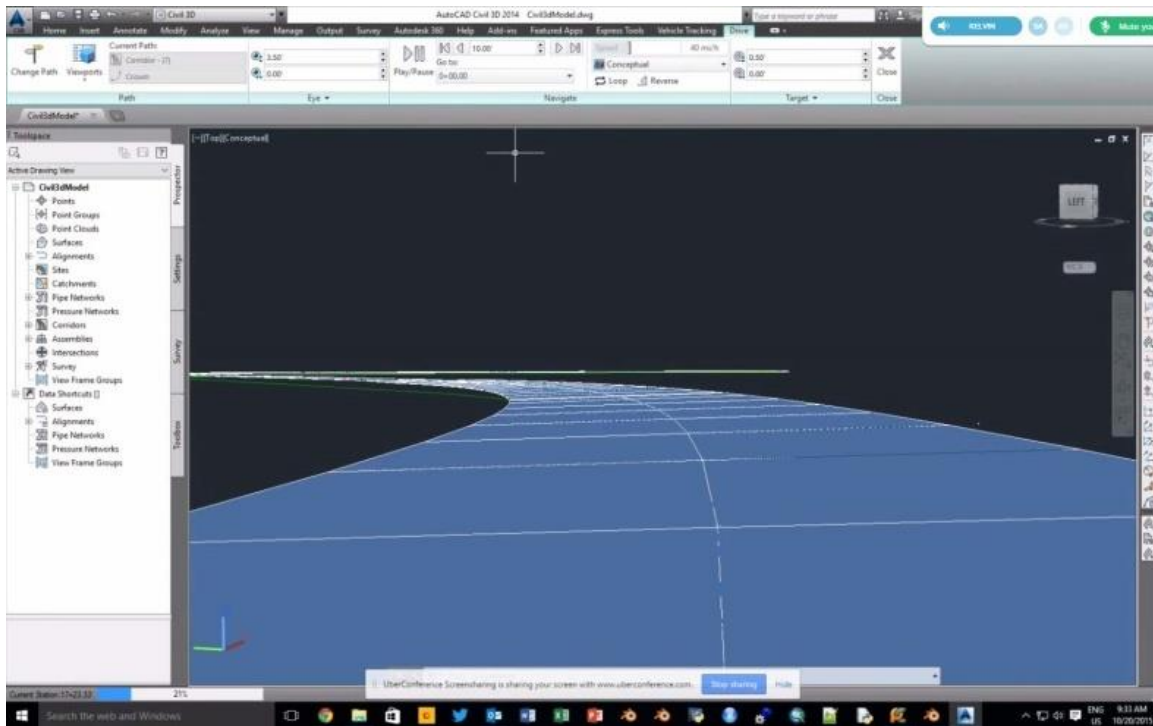
**Figure 2.6 Civil3D roadway**

### 2.1.3 *Generate road model using design parameters*

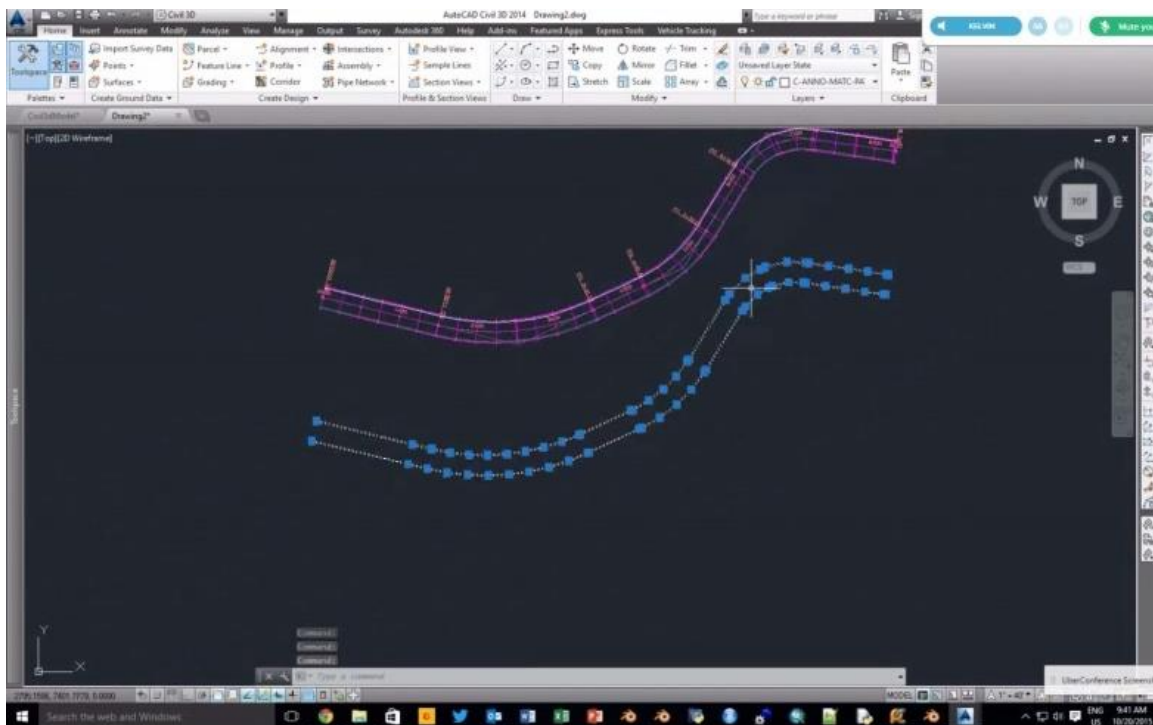
In Civil3D, the road model (Figure 2.7) is generated using an alignment (longitudinal shape) and a corridor assembly (cross-section elements). The corridor assembly in Civil3D corresponds to the NADS lateral curve profile because it is a cross-section of the road. For the SHRP2 model here, the cross-section is level and flat without road crowning, typical of standard roads in the NADS simulator architecture.

### 2.1.4 *Extract Roadway Edge Geometry*

After the generation of surfaces in Civil3D from the design parameters, roadway edge geometry can be extracted from the design model to create the 3D model geometry used within the tile. Road edge geometry is shown in Figure 2.8.



**Figure 2.7 Road surface model in Civil3D**



**Figure 2.8 Edges extracted from road model**

Road data extraction begins by exporting road points to an Excel file using CadTools from Autodesk Civil3D; this step generates data that is segregated into segments

describing a cross-section of roadway. Comparable segments may be collapsed since a lateral profile that doesn't change is effectively constant. The resolution of each segment depends on surface elevation or material changes as shown in Table 2.1. This concept is consistent with the NADS lateral profile, which uses segments to define local surface elevation and surface material type as shown by the record for RURAL\_LN2.

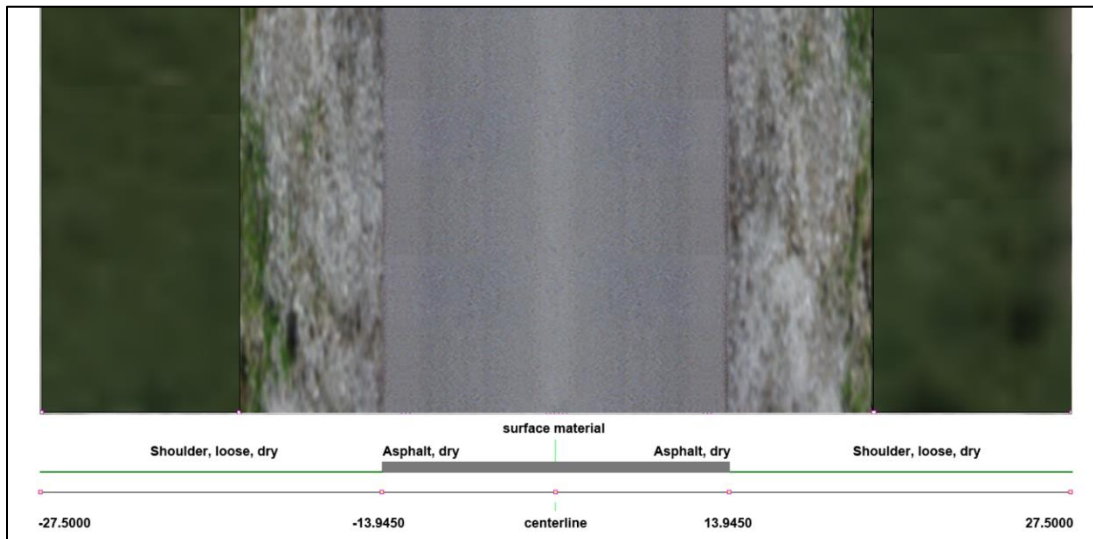
**Table 2.1 Lateral profile for RURAL\_LN2**

Keyword	Unique curve name	Keyword	Width (numeric float)
CurveName	RURAL_LN2	Width	55.00
Keyword	Offset from center	Elevation	Surface material code
Data	-27.50	0.00	777
Data	-13.94500	0.00	777
Data	-13.94500	0.00	262
Data	13.94500	0.00	262
Data	13.94500	0.00	777
Data	27.500000	0.00	777

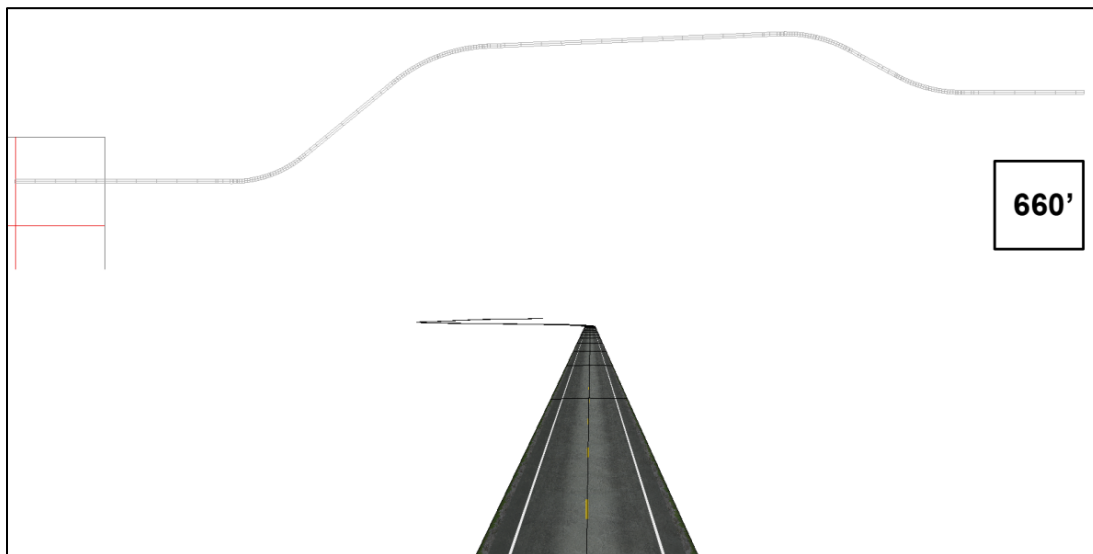
Each unique lateral profile contains data for a roadway cross-section with a point delta from the roadway centerline, an elevation, and a surface material code that can be used by the NADS simulator dynamics engine. In the example above, material code 777 corresponds to a loose, dry shoulder, and code 262 corresponds to mild, dry asphalt. The resultant curve profile is illustrated in Figure 2.9.

### *2.1.5 Format road data using Python scripts to comply with NADS LRI specifications for lateral curve profiles*

The exported data must be further processed to convert it into appropriately formatted records, and can then be integrated into the NADS simulator architecture. In addition to data processing, Python scripts convert the extracted data to a simple 3D Wavefront OBJ file containing road surface geometry with texture mapping applied.



**Figure 2.9 NADS lateral curve profile**

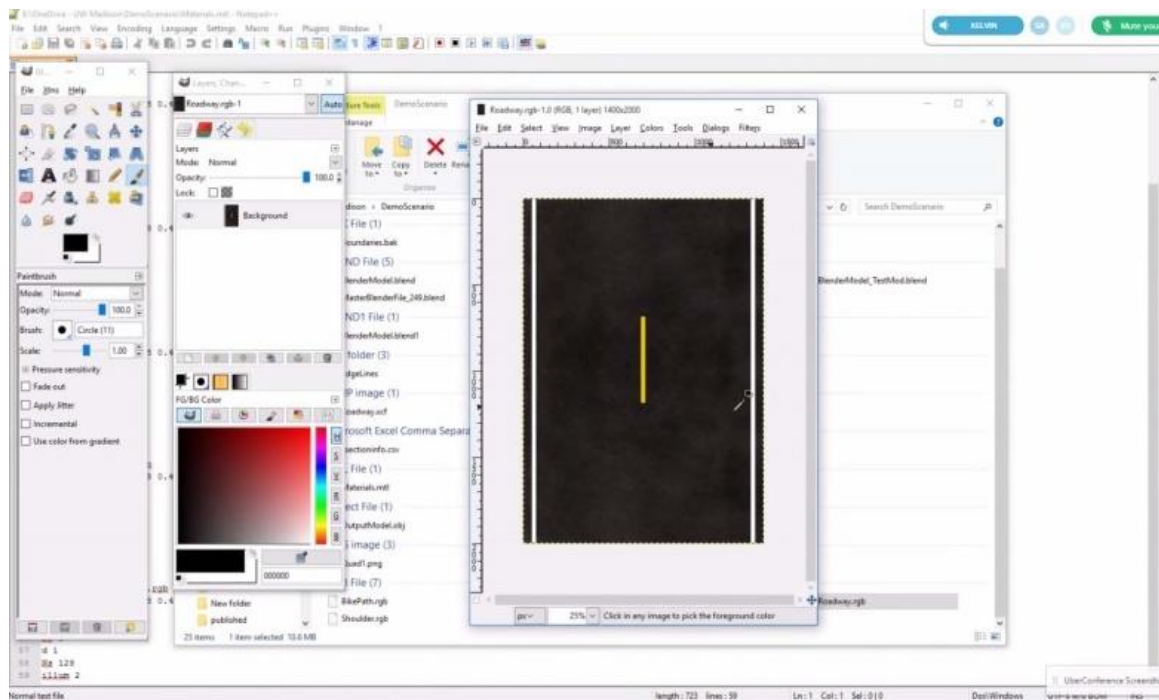


**Figure 2.10 The imported model**

**2.1.6 Create texture placeholders using a bitmap editor (Adobe Photoshop, GIMP, etc.)**

Texture is an image that creates a higher level of detail in a 3D model. Using appropriate features such as road markings, texture provides visual cues necessary for driver navigation of the road network. Textures are two-dimensional and must be applied to 3D geometry to result in textured 3D geometry. Texture mapping is a fundamental graphics technology that is widely available in commercial and free 3D modelling

applications (e.g., Blender, 3DStudio Max, Presagis Creator). These applications also are capable of importing or reading the OBJ file format.



**Figure 2.11 Texture map**

### 2.1.7 Create Model Footprint.

Using a 3D editor, create a tile model footprint that completely encloses the road geometry (see Figure 2.13). The footprint often becomes the basis for tile model terrain surfaces. By convention, roads enter and leave a NADS tile model in the center of a 660-foot edge and are flat and level at that point.

At this point, a small collection of files has been created: tile model geometry, road lateral profiles, and road path files. These files comprise the basis of a tile model but do not yet describe a full tile model. For that to happen, the new tile and associated data must be integrated into the Tile Library and additional features must be built to create a sense of place within the tile, which is described in the next section of this document.

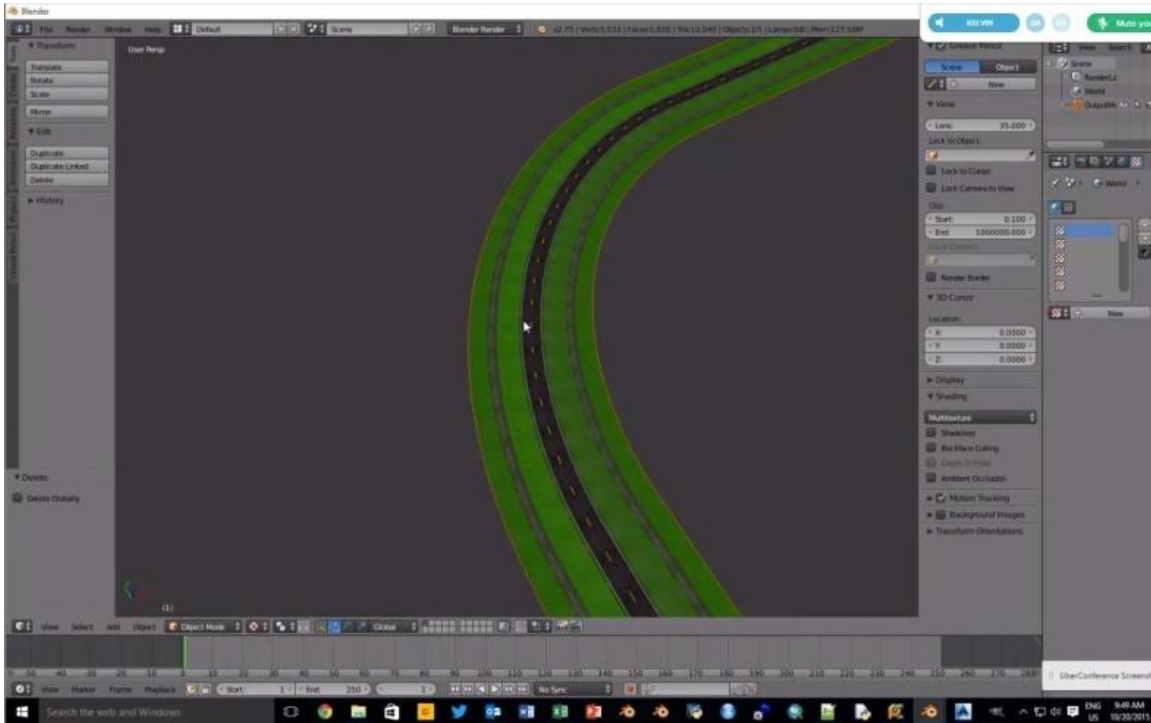


Figure 2.12 Texture applied to road geometry

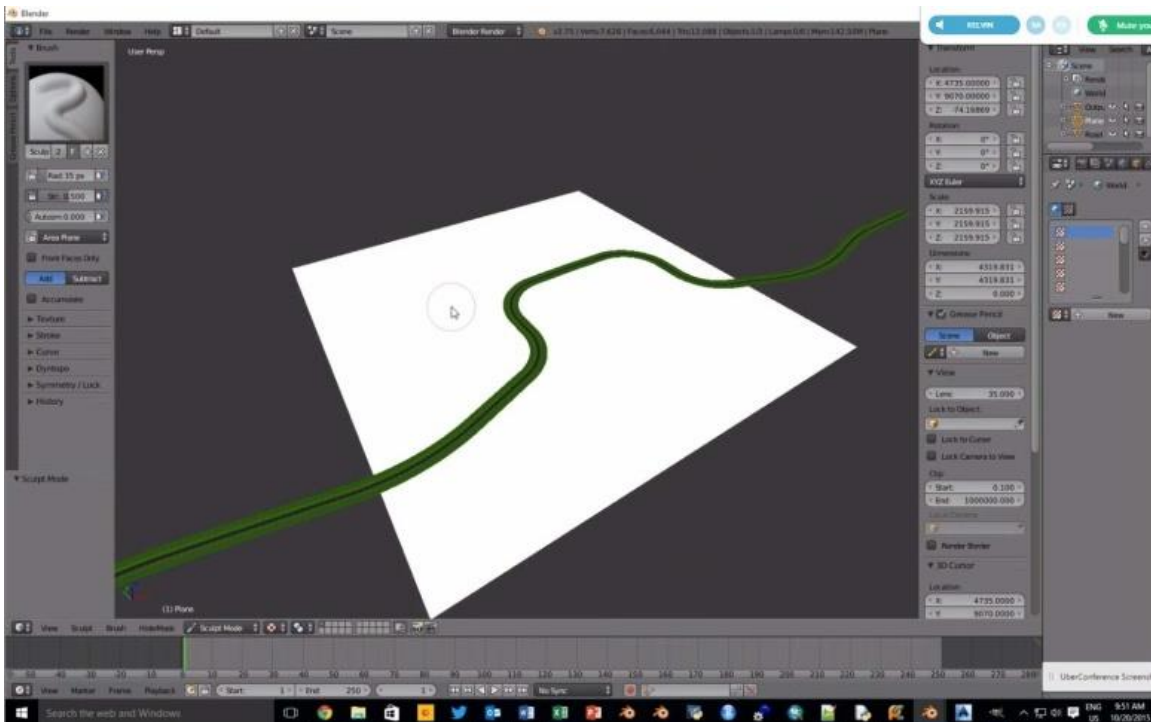


Figure 2.13 Creating a tile footprint using a 3D editor

## 2.2 Construction of additional features within tile model.

This section describes the use of various manual and semi-automated processes to create a drivable tile model from an OBJ file. The process described here can be utilized for any 3D model file intended to be used for driving simulation, and does not necessarily depend on Civil3D.

Using Autodesk Civil3D and a 3D editor, such as Blender, results in a Wavefront OBJ file that contains roadway surface geometry, or what is essentially a road 'ribbon'. Depending on the methods used to generate the road ribbon, the resulting file may or may not be textured. To create a tile model, additional information is needed to define road surfaces, junctions, and other objects, such as signs, as well as additional features.

Tiles follow conventions with respect to dimension, units, orientation, and locations of roads at tile boundaries. Following these conventions makes a tile compatible with the existing tile model library and extends the usability of a tile beyond immediate project needs.

The tile model boundary is defined using standard modeling conventions. A tile can be any size as long as the dimensions are some multiple of 660 feet. Tiles that are several miles in length can best be developed as smaller elements because working on huge regions can become problematic when integrating large numbers of features. As shown in Figure 2.14, the tile footprint is sized to permit easing the road orientation from the real-world curves on the left side back to the center of a tile edge on the right.

Viewing the tile model in the context of the world provides a sense of how large an area the model will occupy, as shown in Figure 2.15. The SHRP2 data tile is highlighted in the upper right quadrant.

Side roads were added to the tile model to create a road network comparable to the real-world location. Satellite imagery was used to place these side roads, and their lateral definition was adjusted to satisfy NADS conventions at each tile edge as shown in Figure 2.16.

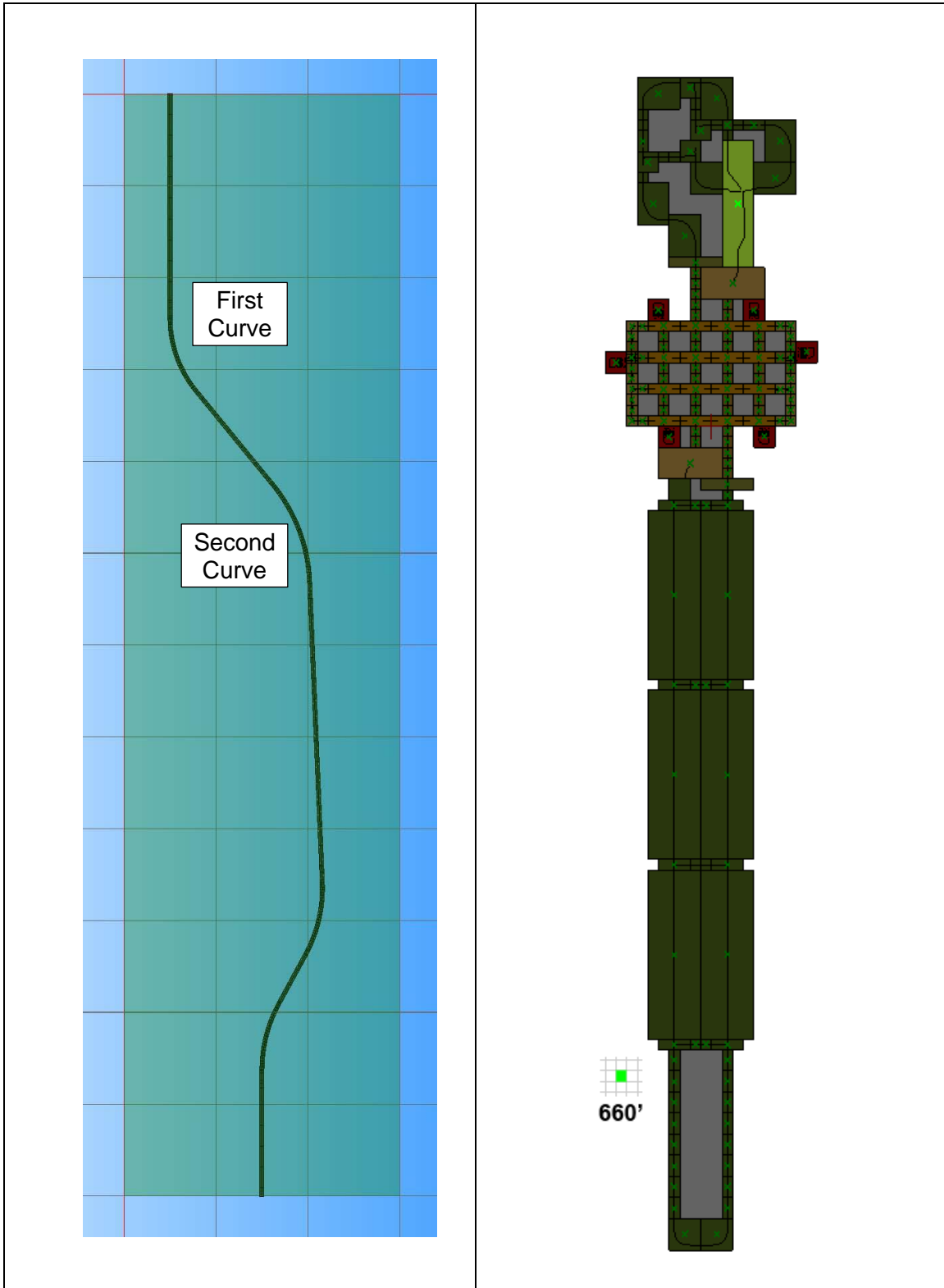


Figure 2.14 Road ribbon and tile model footprint

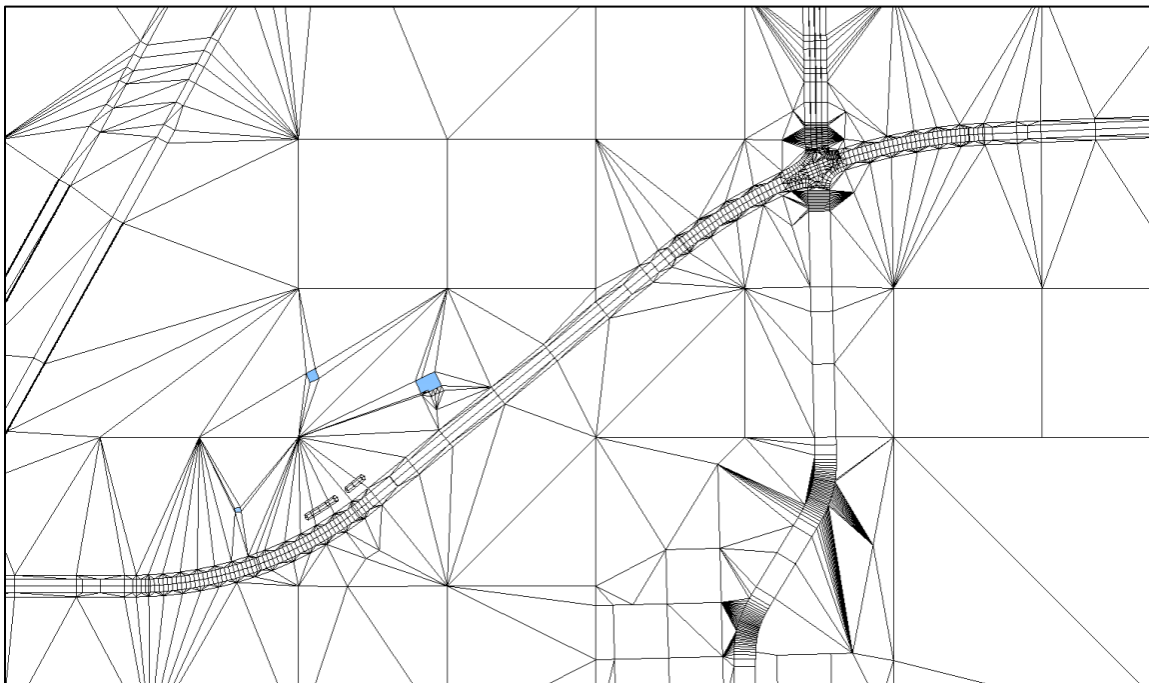
Figure 2.15 World configuration and tile placement





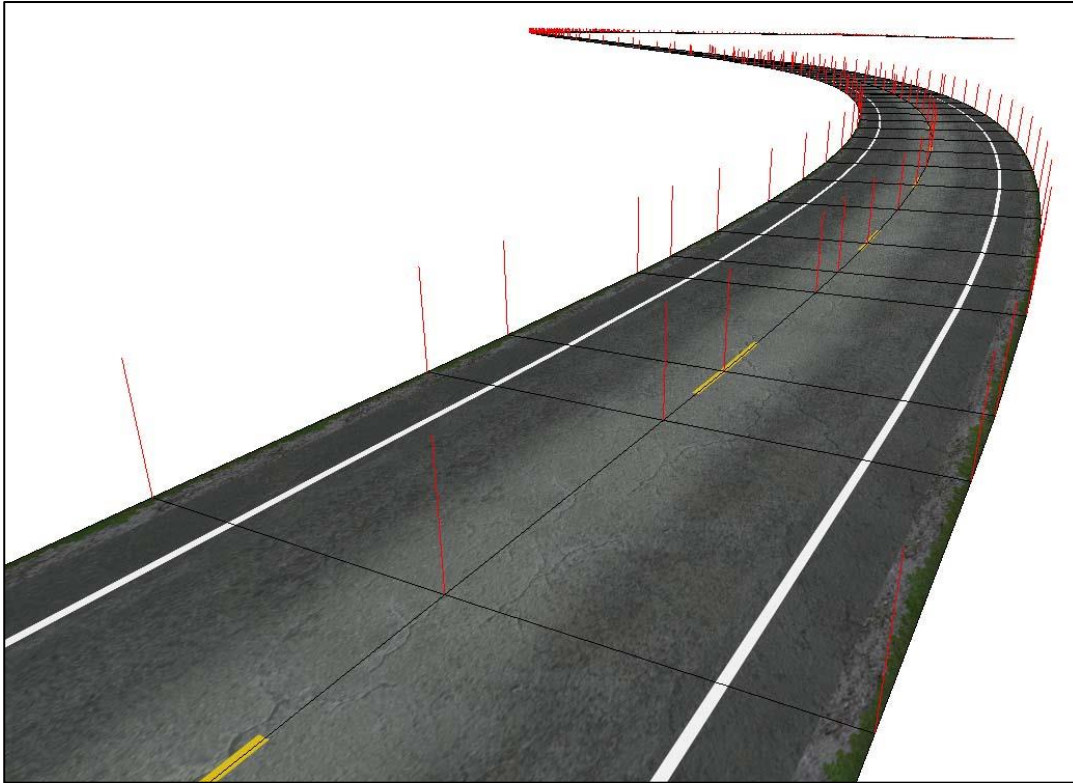
**Figure 2.16 Side road additions**

Terrain geometry is added to the model by first slicing the tile footprint based on a 660-foot grid and then stitching these faces to the road surface edges as shown in Figure 2.17.



**Figure 2.17 Terrain stitched to roads**

Creating road data files from geometry requires vertex normals to provide orientation data for each centerline road point. The shading function within the 3D editor assigns normals to each vertex, as shown by the red vectors in Figure 2.18. Vectors are essential to fully describe the surface orientation in three-dimensional space at each point in the road centerline.



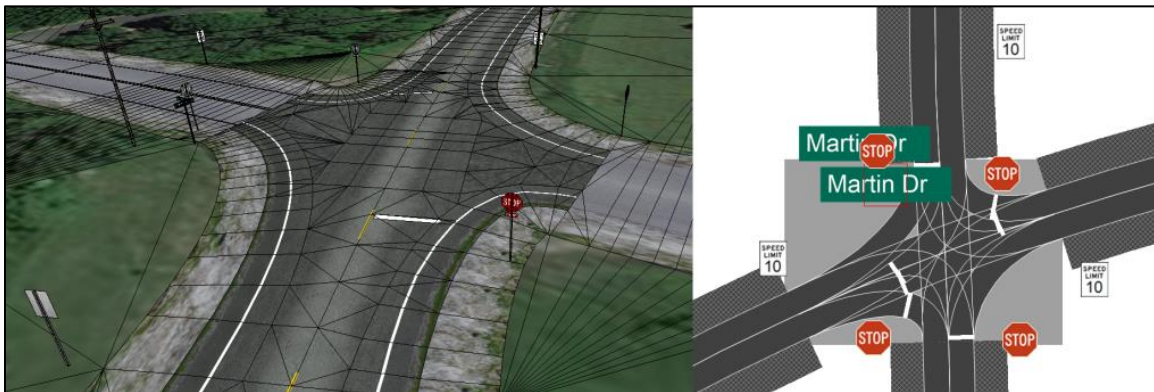
**Figure 2.18 Shaded ribbon showing red vertex normal**

Road centerline data can be extracted from the model following the assignment of vertex normals (shading). This process takes the form of extracting “XYZ, ijk” from the model geometry using the points along the center of each road. In Creator™, this step can be accomplished by selecting the centerline vertices and generating a report in HTML format. This data can be processed semi-automatically using scripts to filter unique, sequentially ordered points. The data is finalized by re-formatting the coordinate data with keywords and adding path or corridor fields. The proper format is shown in Table 2.2.

**Table 2.2 Centerline path or corridor data file**

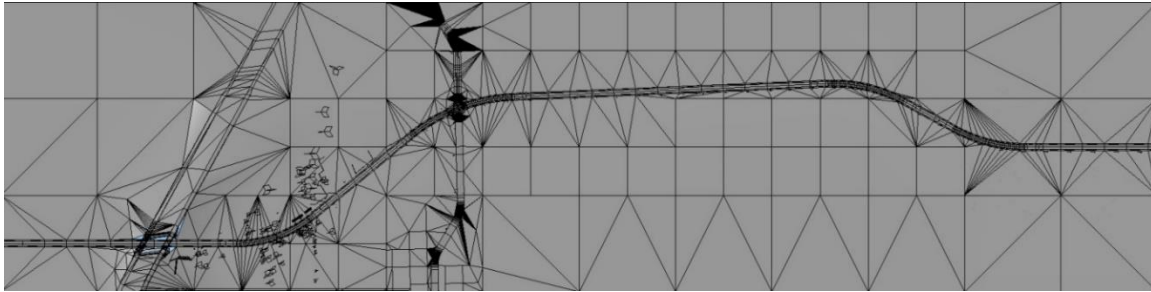
Keyword	Point coordinate axis data (position)			Point normal components (orientation)		
	X	Y	Z	i	j	k
POINT:	0.00	330.00	0.00	0.128196	0.000123	0.991749
POINT:	150.00	330.00	0.00	0.122789	-0.000010	0.992433

Objects and attributes are added to the model following NADS conventions. This is a manual process with some semi-automated steps. This information is embedded within the tile model to ensure accurate correlation between the visual and virtual model and processed during the production of world visual and correlated virtual data files. Detailed object and attribute information is documented in the Logical Road Information (LRI) specification document. Embedded data can be visualized within the interactive scenario authoring tool (ISAT), shown below in Figure 2.19.


**Figure 2.19 Visual model and ISAT view**

After the basic model has been developed and integrated into the NADS tile model library, it can be used in the production of simulator worlds. At this point, however, the model is very basic and consists only of roadway, intersection, and basic terrain (Figure 2.1, Figure 2.20).

It is necessary to add features to the model in order to create a more believable environment. The number and detail of features has a direct bearing on the complexity and believability of the model. A higher degree of complexity and detail typically results in greater immersion during simulation. Adding features is a manually intensive process, especially if no assets (i.e., preexisting simulator features) exist that are representative of the real-world features.



**Figure 2.20 Basic tile model**

Due to the need to replicate a real-world location, Google Earth is used to determine the location, number, and complexity of features adjacent to the roadway. Both overhead and street views are used to identify and develop tile features. Custom texture maps are generated to create a tile model that is consistent in look and feel with the real-world location. Priority is given to features that are adjacent to the road and contribute to replicating the real-world environment. Due to time and budget constraints, some features are re-used instead of being created to correspond to all real-world features.

In Figure 2.21 below, pine trees were created by modifying Google Earth street view imagery to produce features consistent with the real-world location. Originally built for trees located on berms, these features were re-used by scaling them larger to provide another row of trees without requiring all unique tree features.

The screen captures in Figure 2.22 show the 3D model on the left and the Google Earth street view on the right during development of pole, sign, mailbox, vegetation, and wall features.



**Figure 2.21 Custom features (top) and re-purposed (bottom)**



**Figure 2.22 Model vs. reference, left to right**

### 3 NADS-1 Data Collection

#### 3.1 Participants

Sixty-one drivers participated in the study. Drivers were recruited from two age groups, younger (aged 21-45) and older (60-80). Age groups comprised an equal distribution of male and female participants. Participants were divided into two groups, one group that performed a secondary text entry task (described below) and one group that did not. Demographic information is provided in Table 3.1. Procedures were approved by the University of Iowa Institutional Review Board, and all participants provided informed consent prior to participation. Participants were asked (after the simulated drive) about their previous experience with unintended acceleration (UA). Nine of the sixty-one drivers reported having experienced a UA event, with most of these events taking place during parking maneuvers.

**Table 3.1. Demographic information and experimental design**

<b>Event A: Parking Event (N=32)</b>			
Young		Old	
Male	Female	Male	Female
N = 8 Age (M) = 29.5 Age range = 21-45	N = 8 Age (M) = 30.6 Age range = 21-45	N = 8 Age (M) = 67.6 Age range = 60-74	N = 8 Age (M) = 69.3 Age range = 65-79

<b>Event B: Left Turn (N=29)</b>			
Young		Old	
Male	Female	Male	Female
N = 6 Age (M) = 32.8 Age range = 26-43	N = 7 Age (M) = 29.4 Age range = 24-40	N = 8 Age (M) = 67.0 Age range = 61-73	N = 8 Age (M) = 67.1 Age range = 62-79

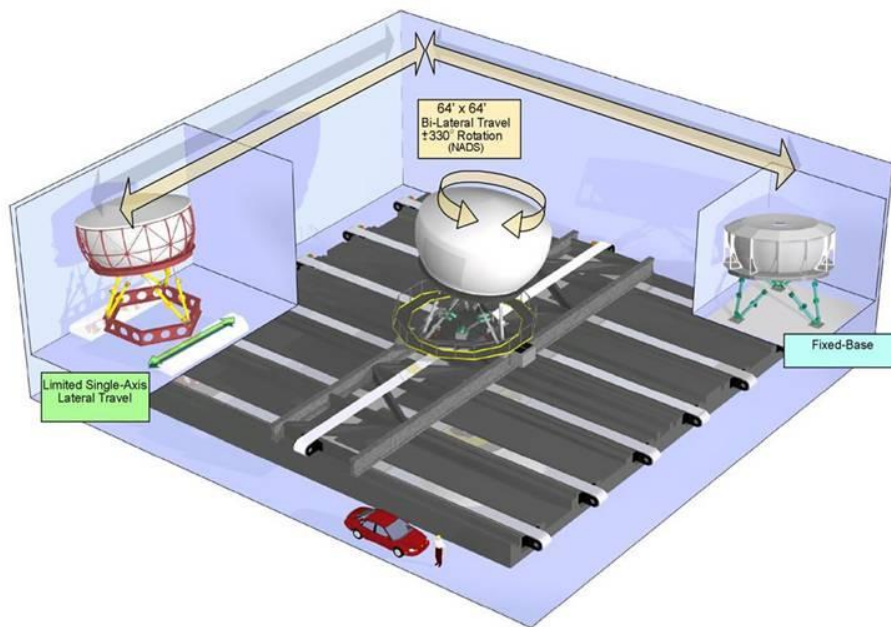
Data were collected on the NADS-1 driving simulator at the UI (Figure 3.1). The NADS-1 simulator consists of a 24-foot-diameter dome that encloses a full-size sedan. The 13-degree-of-freedom motion system provides accurate acceleration, braking, and steering cues to drivers as if they were actually driving. The NADS-1 uses sixteen high-definition (1920x1200) light emitting diode (LED) projectors to display seamless imagery on the interior walls of the dome with a 360-degree horizontal and 40-degree vertical field of view. The simulator cab is a 2014 Toyota Camry equipped with active feedback on steering, brake and accelerator pedals, and a fully operational dashboard. Data were sampled at 240 Hz.

### 3.2 Experimental Design

The study manipulated three independent factors across two distinct study events. Given the emergency nature of the UA events, drivers were exposed to only one of the two events, either the Parking event or the Left Turn event. Age group (young, old), gender (male, female), and distraction (distracted, undistracted) comprised the other between-subjects independent variables. The experimental design is summarized in Table 3.1.

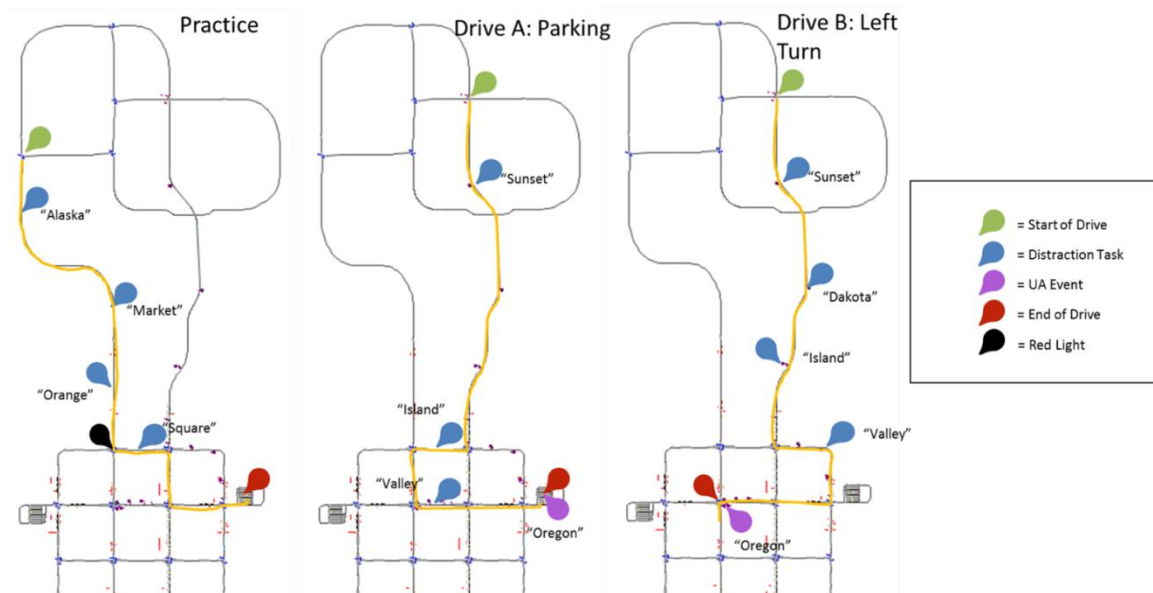
### 3.3 Driving Scenario

The simulator test consisted of an approximately fifteen-minute drive along a predetermined route in the Springfield virtual database (<https://www.nads-sc.uiowa.edu/springfield/>). The drive started in a rural section and ended in an urban environment (Figure 3.2). The route was meant to mimic a typical commute, and light ambient traffic was included throughout the drive. During the drive, participants received auditory cues for navigation as well as to complete the secondary text entry task (described below). The study drives concluded with the UA event, either in a commercial parking lot or at an intersection during a left turn.



**Figure 3.1. Exterior (top) view of the NADS-1 simulator (top), diagram of NADS-1 range of motion (middle), and interior view of the cab (bottom)**

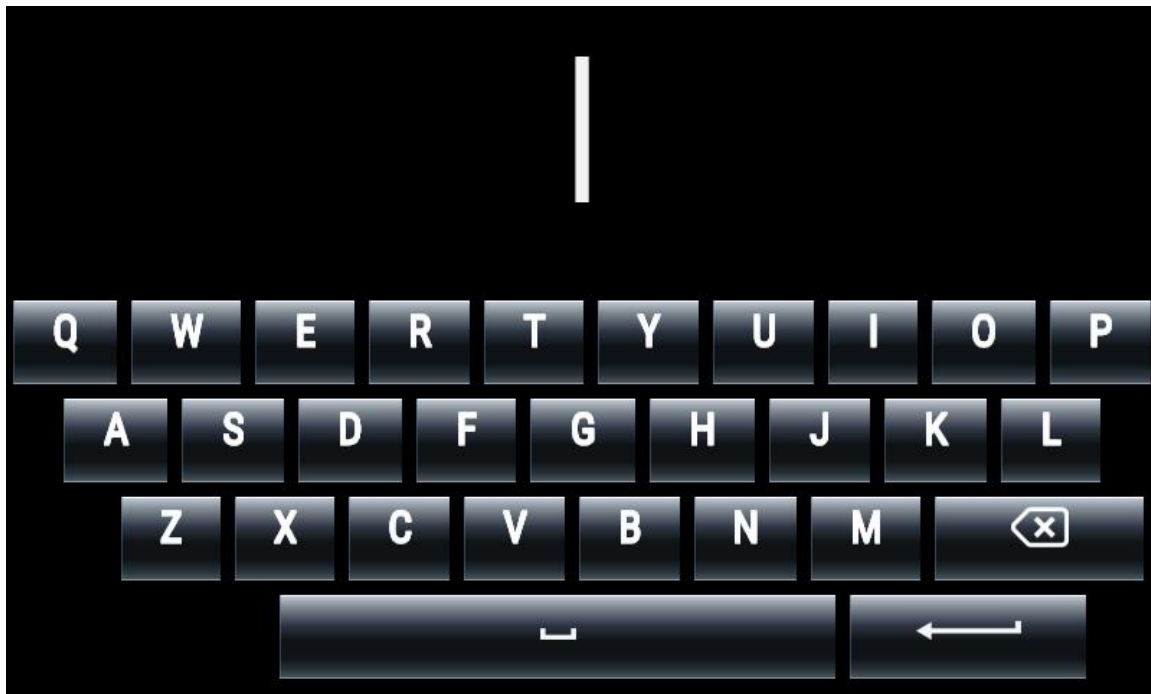




**Figure 3.2. Route maps for the practice and study drives**

### 3.3.1 Secondary Text Entry Task

To examine how distraction affects UA responses, half the participants were asked to perform a visual-manual text entry task prior to the onset of the UA event (Figure 3.3). Drivers were prompted to enter a word (e.g., “Alaska”) and had to type the word on the center infotainment touchscreen display. Drivers encountered several other filler distraction tasks in earlier portions of the practice and study drives to familiarize them with the task. Post-hoc video review indicated that drivers were hesitant to engage in the distraction task during the parking and left-turn maneuvers. The following results therefore exclude the role of distraction in driver response behavior.



**Figure 3.3. Secondary task touchscreen display**

#### 3.4 Procedure

Prior to the study drive, participants completed a five-minute practice drive, during which they made several right and left turns and practiced braking maneuvers and parking. The practice drive served to acquaint participants with the driving simulator and screen for simulator sickness. Wellness scores were collected after both the practice and study drives. The early portion of the study drives served to further acclimate drivers to the simulator and vehicle controls and provide filler events so the driver did not anticipate the UA event at the end of the drive. At the end of the drive, drivers encountered one of two UA events, as described above.

## 4 NADS-1 Results and Discussion

### 4.1 Data Reduction and Summary Measures

Data were reduced using custom Matlab software. The measures of interest are described in Table 4.1. We were particularly interested in behavior during two periods, approaching the curve and during the curve. Measures of interest included both vehicle control (speed, steering) and vehicle position (lane offset).

**Table 4.1 Summary measures**

<b>Measure</b>	<b>Unit</b>	<b>Description</b>
Approach Speed	Mph	Mean speed approaching the curve, prior to entrance.
Mean Speed	Mph	Mean speed during the entire curve.
Change in Velocity	Mph	Difference in velocity between curve entrance and midpoint. Negative values indicate a speed reduction.
SD Speed	Mph	Standard deviation in speed during the entire curve.
SD Steer	Degrees	Standard deviation in steering wheel angle during the entire curve.
Lane Offset	ft	Mean offset from the center of the lane. Positive values indicate right offset and negative values indicate left.
SD Lane Position (SDLP)	ft	Standard deviation in lane position.
Change in lane position	ft	Difference in lane position between curve entrance and midpoint. Positive values indicate a shift right.

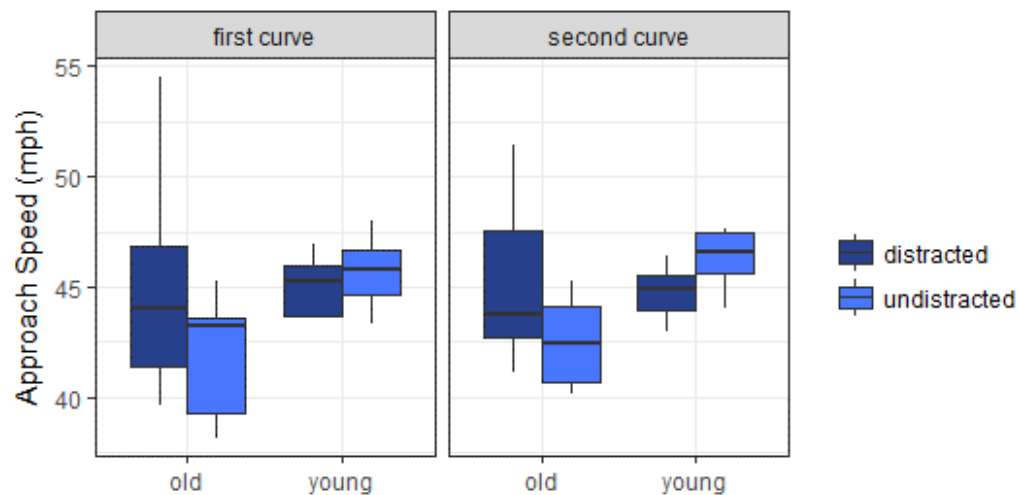
### 4.2 Overview

The goal of this analysis was to identify the effects of age, gender, and secondary task condition, and their interactions, on driver behavior while driving the naturalistic curves. Summary measures were analyzed using ANOVAs with age, gender, and condition as between-subjects factors. Bonferroni-adjusted paired comparisons were conducted, where appropriate, to examine differences between multiple levels of a factor

or combinations of factors. The following plots visualize the data as boxplots representing the median, first, and third quartile range, and outliers. The following tables include the main effects for each independent variable along with significant interactions of interest.

### 4.3 Approach to Curves

Approach speed was calculated during the 100 ft preceding curve entry. There was a significant main effect of age, with older drivers approaching slower than younger drivers, particularly those older drivers who were undistracted, as evidenced by a significant age by condition interaction (Figure 4.1).

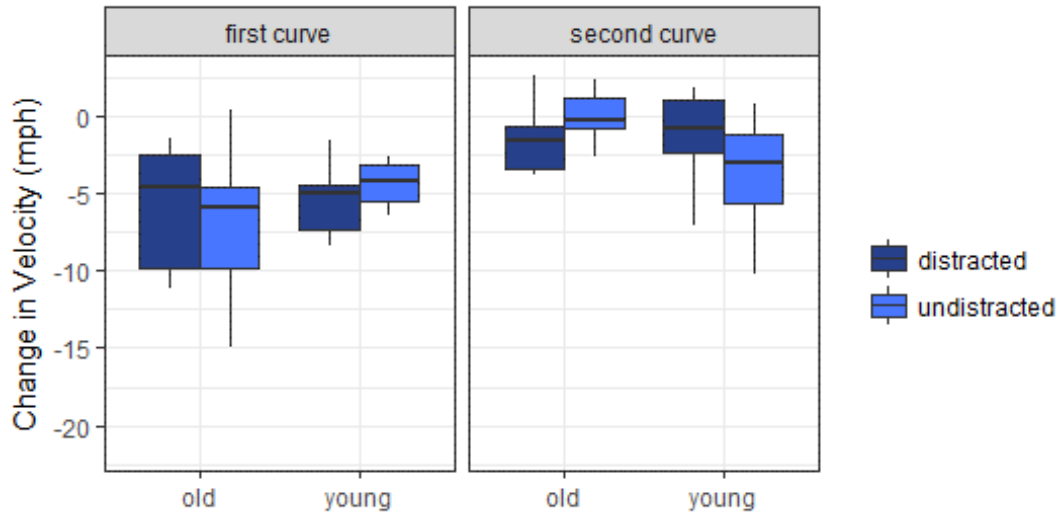


Factor	F(1,52)	p
Age	5.30	0.003*
Gender	0.27	0.61
Condition	2.77	0.10
Curve	0.36	0.55
Age*Condition	8.42	0.01*

**Figure 4.1 Curve approach speed**

The change in velocity was calculated as the difference in speed from the start of the approach to the midpoint of the curve. There was a significant main effect of curve, with

drivers reducing their speed more in the first curve than in the second curve. This was particularly true for older drivers, who reduced their speed more than younger drivers in the first curve but showed an equivalent speed reduction as younger drivers during the second curve (Figure 4.2).

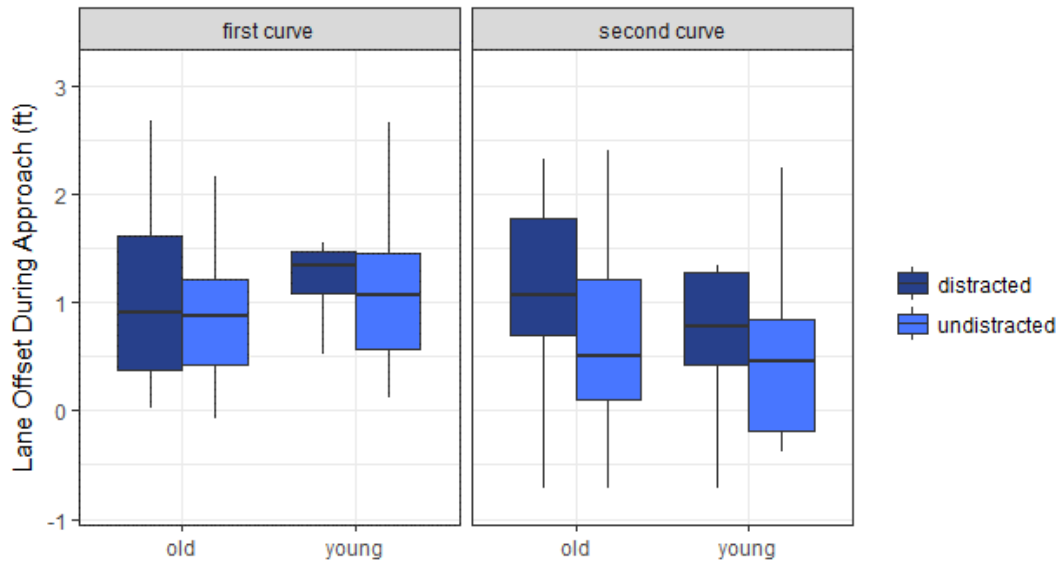


Factor	F(1,52)	p
Age	0.17	0.68
Gender	0.04	0.85
Condition	0.01	0.93
Curve	17.16	<0.001*
Age*Curve	3.52	0.07*

**Figure 4.2 Change in velocity on curve approach**

Lane offset was calculated as the distance in feet from the center of the right lane. Negative values indicate shifts to the left, and positive values indicate shifts to the right. Approach lane position was calculated over the same interval as approach speed. As seen in Figure 4.3, drivers were positioned to the right of the centerline, as indicated by the positive lane offset values. There was a main effect of secondary task condition such that distracted drivers shifted farther in the lane during approach than undistracted

drivers. This shift to the right was more pronounced during the first curve than the second, as drivers tended to shift back toward center.

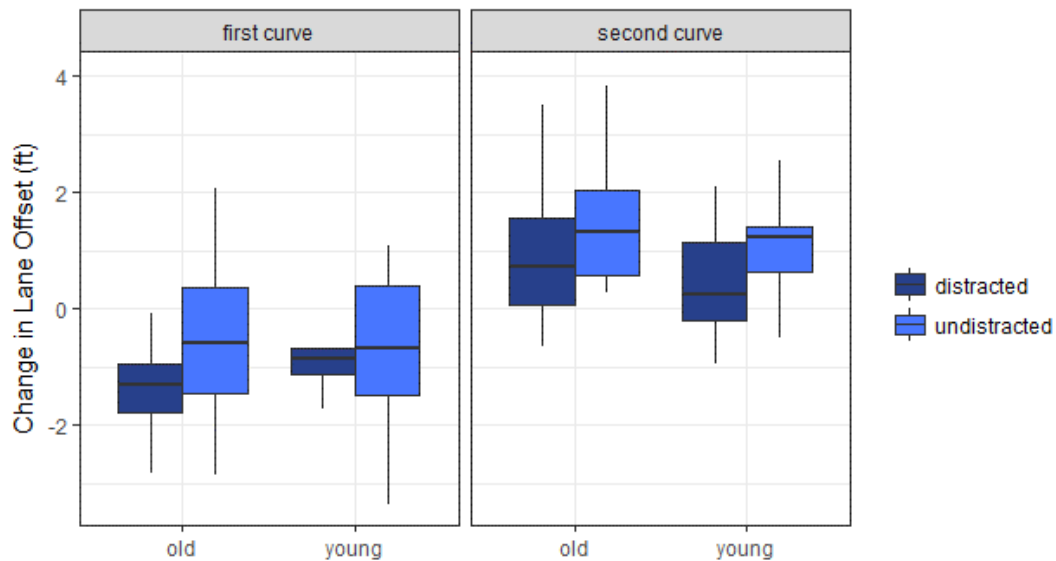


Factor	F(1,52)	p
Age	0.03	0.87
Gender	0.16	0.69
Condition	4.09	0.05*
Curve	5.17	0.02*

**Figure 4.3 Lane offset during curve approach**

The change in lane position was calculated using the same points as the change in speed calculation. There was a significant difference between the two curves, such that in the first curve drivers tended to shift left, and in the second curve drivers shifted right (Figure 4.4). This was expected given the opposite direction of travel in the two curves, and the effect indicates that drivers tended to shift toward the center of the lane. Importantly, there was a significant main effect of secondary task condition, with distracted drivers shifting farther to the left and undistracted drivers shifting farther right. Interestingly, this effect was consistent across the two curves, suggesting that perhaps

distracted drivers tended to always shift back toward the center of the road, regardless of curve direction.



Factor	F(1,52)	p
Age	0.94	0.34
Gender	0.70	0.40
Condition	5.00	0.03*
Curve	77.21	<0.001*

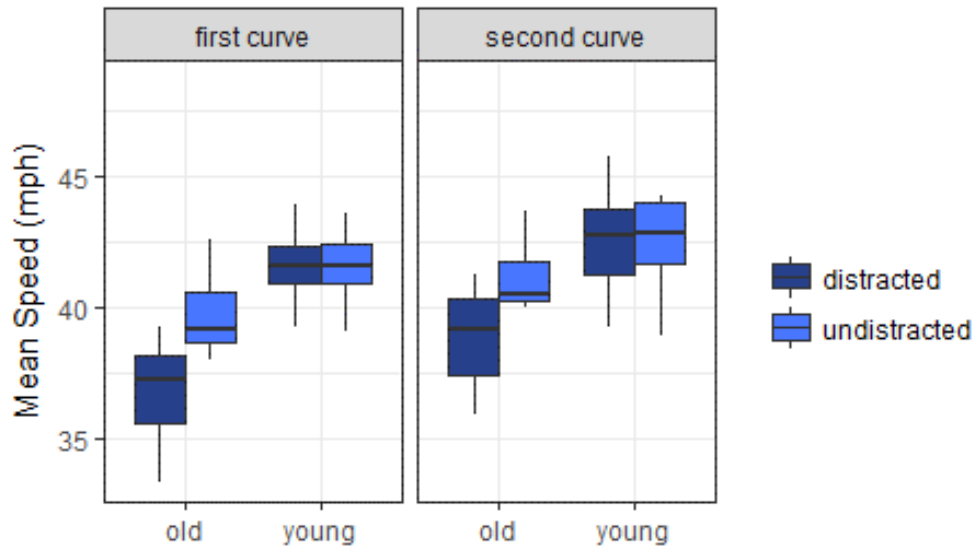
**Figure 4.4 Change in lane offset**

#### 4.4 Behavior in Curves

During the curves, distraction resulted in significantly higher speed than driving without the secondary task. Older drivers also drove slower than younger drivers. Importantly, there was a significant age by condition interaction whereby older drivers showed a significantly greater decrease in speed in the undistracted condition compared to the distracted condition than did younger drivers. Speed tended to increase from curve one to curve two.

Hallmark and colleagues (2014) developed a model of driver behavior in rural curves based on the SHRP2 data. Importantly, this model suggested that for every ten-year

increase in driver age, there was an expected reduction of 0.5 mph in speed. For the current sample, the groups were separated by approximately 40 years, which would thus predict a 2 mph difference in speed between younger and older drivers. Figure 4.5 shows that this prediction holds with the present simulator data, suggesting that behavior in these curves was at least fairly consistent with driver models based on naturalistic data. Furthermore, the model indicated that distraction was associated with a 3.3 mph reduction in speed relative to no distraction. This result also appears to hold in the simulator results, at least in the case of the older drivers. It is worth reiterating here that younger drivers showed considerably less difference between the distracted and undistracted conditions with respect to speed.

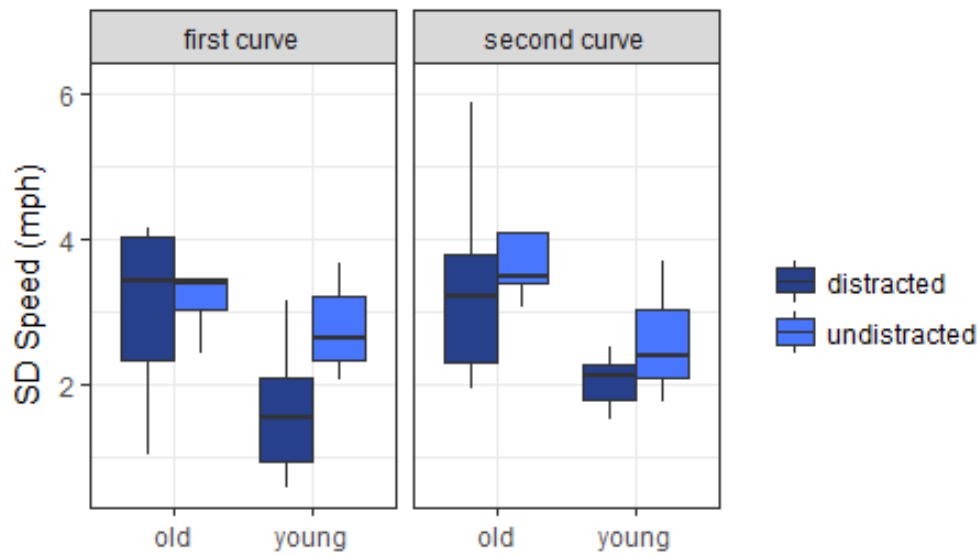


Factor	F(1,52)	p
Age	21.00	<0.001*
Gender	0.10	0.76
Condition	5.74	0.02*
Curve	3.96	0.05*
Age*Condition	6.37	0.01*

**Figure 4.5 Mean speed during curves**



Standard deviation in speed was used as an index of variability in speed maintenance during the curve. Somewhat surprisingly, distraction resulted in a significant decrease in speed variability during the curve, demonstrated by a significant main effect of condition. Figure 4.6 shows that this effect was driven primarily by younger drivers in the first curve, where distracted drivers showed much less variability than undistracted drivers. Variation in speed also increased slightly from the first to second curve.

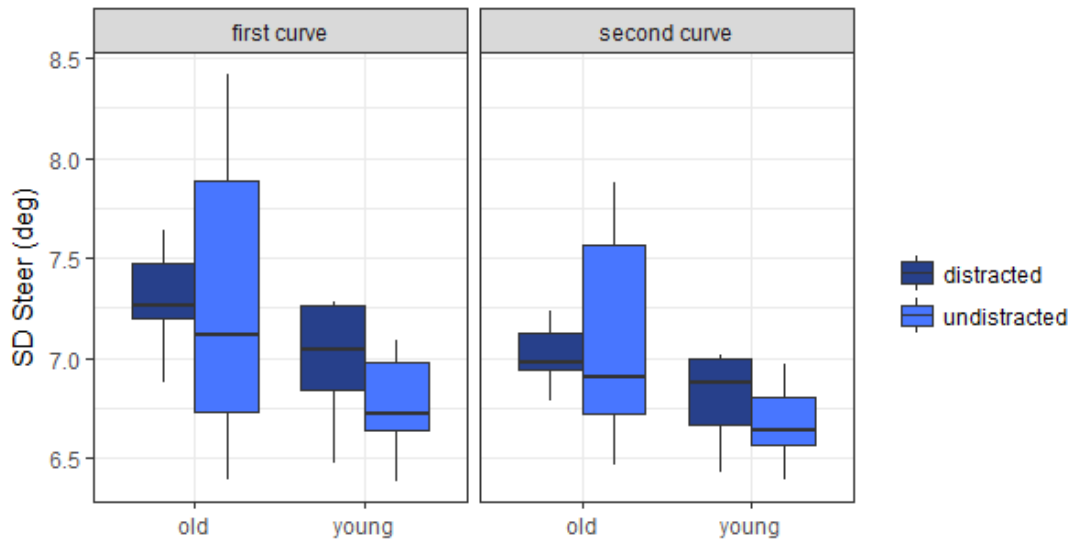


Factor	F(1,52)	p
Age	0.25	0.62
Gender	0.17	0.68
Condition	4.92	0.03*
Curve	5.15	0.03*

**Figure 4.6 Standard deviation of speed during curves**

Standard deviation in steering provides a metric of steering wheel manipulation during curve driving. As seen in Figure 4.7, older drivers tended to show greater variability in steering wheel angle than younger drivers across both curves and task

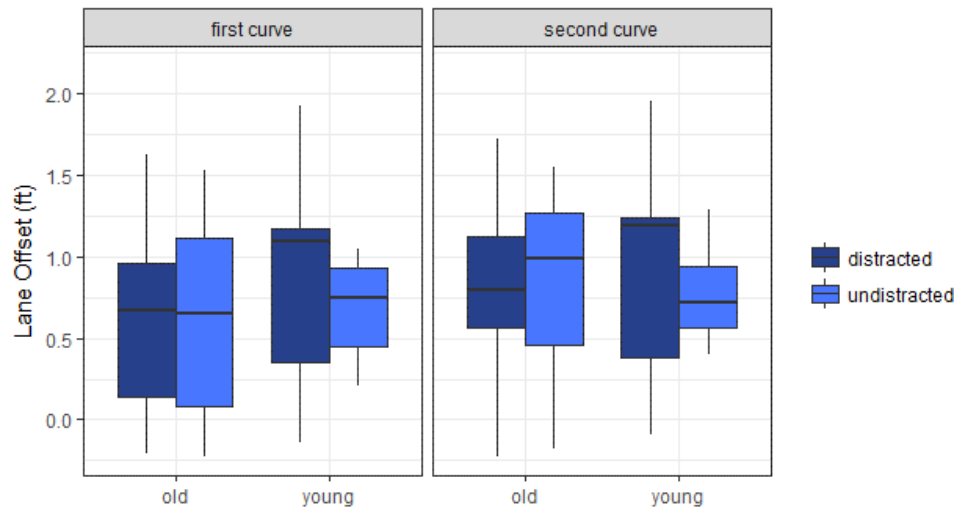
conditions. This indicates that older drivers were manipulating the steering wheel to a greater extent than younger drivers.



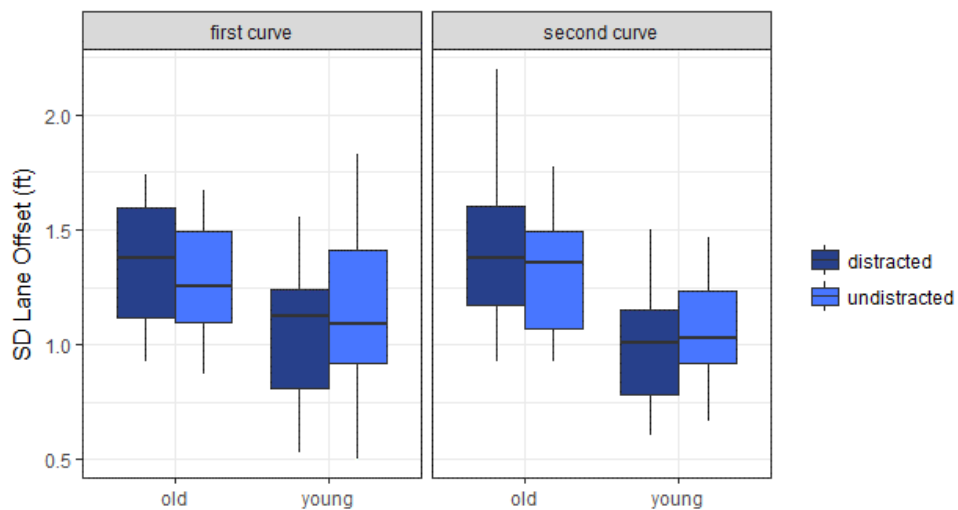
Factor	F(1,52)	p
Age	15.86	<0.001*
Gender	0.11	0.74
Condition	0.84	0.36
Curve	4.13	0.05*

**Figure 4.7 Standard deviation of steering wheel angle**

Curve position was again measured by offset from the center of the right lane. As shown in Figure 4.8, there was not a significant difference between the two curves with respect to position. Furthermore, neither distraction nor driver age resulted in a significant difference in lane positioning. For variability in lane position during the curve, measured by standard deviation in lane position, only driver age yielded a significant main effect, as seen in Figure 4.9. Younger drivers tended to drive closer to the center of the lane, on average, compared to older drivers. Variability in lane position was similar across both curves and distraction conditions.



Factor	F(1,52)	p
Age	2.36	0.13
Gender	0.09	0.77
Condition	0.13	0.71
Curve	2.03	0.16

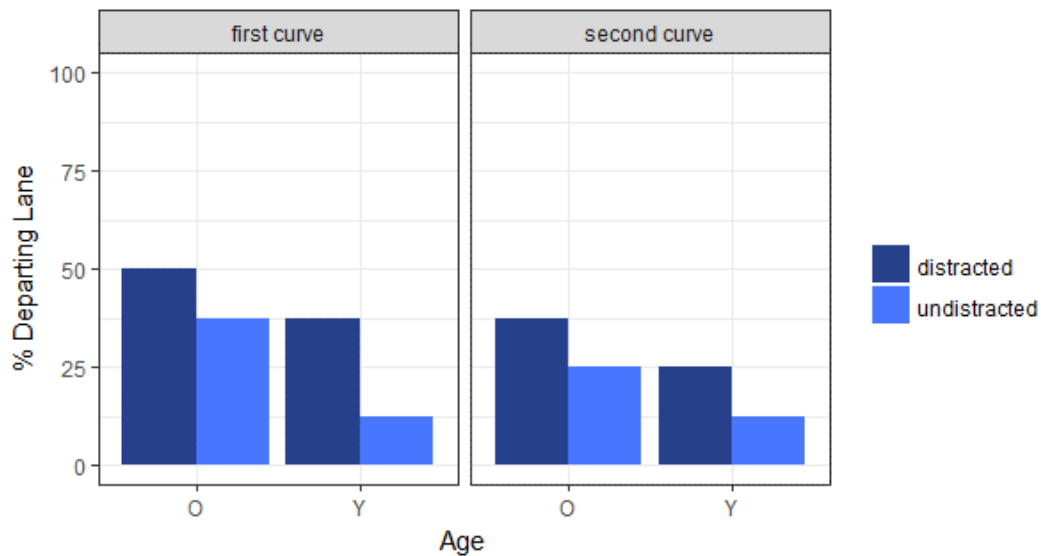
**Figure 4.8 Lane offset during curves**


Factor	F(1,52)	p
Age	19.56	<0.001*
Gender	0.21	0.65
Condition	0.01	0.92
Curve	1.13	0.29

**Figure 4.9 Standard deviation of lane offset during curves**

#### 4.5 Lane Departures

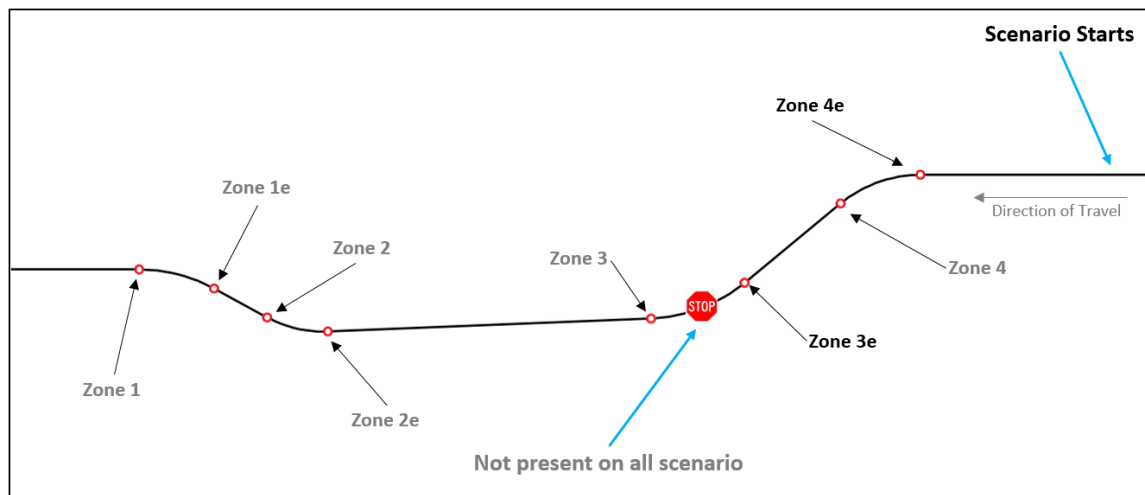
An important question is the extent to which drivers were likely to depart the lane during curve negotiation. Lane departures are serious and potentially hazardous driving events that can lead to loss of control and single-vehicle run-off-road crashes. Lane departures were defined as any of the wheels crossing a lane boundary, either left or right. It is worth noting that, as expected based on previous research, a majority of the lane departures were toward the outer portion of the curve (i.e., to the driver's right, away from oncoming traffic). See Figure 4.10 for the percentage of drivers who departed the lane during curve negotiation.



**Figure 4.10 Percentage of drivers departing lane during curves**

## 5 Pilot Experiment on UW-Madison Driving Simulator

A smaller version of the scenario was pilot-tested using a full-scale driving simulator at the University of Wisconsin-Madison. A schematic of the scenario based on the SHRP2-derived curve data is shown in Figure 5.1. A slightly different version of the scenario, without a stop sign between Zone 3e and Zone 3, was used for 25% of the subjects; the slightly different version also had a start point further upstream of the one shown in Figure 5.1. In the figure, key areas of interest are Zone 4e and Zone 3e. Speed measurements at Zone 4e can be compared with speeds reported for the “first curve” in the NADS experiment, while speeds reported for Zone 3e can be compared with the speeds reported for the “second curve” in the NADS experiment.



**Figure 5.1 Schematic of UW-Madison Scenario**

Road geometry for the tile containing SHRP2-derived curves was identical to the tile of the NADS experiment. In fact, the same base 3D model was used for creating the scenario. The scenario creation process, the nature of the experiment, and the results are discussed in the sections ahead.

## 5.1 Scenario Creation Process

The tile created for the NADS experiment was adapted to run on the UW-Madison driving simulator that runs on the Real Time Technologies (RTI) platform. Scenario models initially developed independent of the platform and then converted to the required NADS format were available in OBJ format. These models were converted to VRML format for compatibility with the Internet Scene Assembler tool used to create scenarios for the RTI platform.

In order to make the NADS tile compatible with the RTI platform, tile components required streamlining. Model streamlining was required due to the use by NADS of a larger number of polygons, different units, different texture formats, scenario component switches, and different metadata to define roadway surfaces.

At the end of the streamlining process, a tile with the same roadway geometry but with a simplified roadside was available for the UW-Madison experiment. Differences in the roadside environment that were the result of the streamlining process include the use of different building models as well as the use of different vegetation models. Figure 5.2 shows a photograph of the tile running on the UW-Madison driving simulator.



**Figure 5.2 Photo of Tile Running on UW-Madison Simulator**

### 5.1.1 *Recommendations for Tile Compatibility*

Sharing scenario tiles across different platforms is a useful approach that allows running experiments on multiple platforms to produce a more diverse dataset that could include geographically distributed observations as well as different subject demographics. However, when creating 3D models for compatibility across different platforms, there are aspects of the process that, if addressed during the scenario planning stages, could make the scenario-sharing process a simpler experience. For example, the common scenario capabilities across platforms should be identified prior to creation of the model. Identifying common capabilities will allow the eventual removal or streamlining of components from an initial model. Additionally, and to the extent possible, common image formats for textures should be identified to avoid having to deal with image conversion processes and the associated challenges. The use of switches to turn features of the scenario on/off should also be avoided as these do not necessarily work across the different scenario authoring tools used by the platforms.

## 5.2 **Experimental Procedure**

A total of 8 subjects were recruited to participate in the pilot experiment conducted at the UW-Madison site. Prior to the experiment, the subjects underwent a signed consent process. Subjects were asked to drive the scenario previously described in Figure 5.1. While some of the subjects drove the scenario in different directions for data exploration purposes, only the direction of travel shown in Figure 5.1 was of interest.

Instructions provided to the subjects prior to the start of the experiment were to drive along the road as they normally would if using their own vehicle. At the end of the route, a road block indicated that they had reached the end of the drive. During the experiments, only the subject was inside the vehicle cabin, while a researcher monitored the experiment from the base station shown in Figure 5.3.



**Figure 5.3 UW-Madison Driving Simulator**

Once a drive was completed, data logs were extracted and cataloged for analysis. Experiment data collected include speed, steering, gas pedal and brake pedal position, timestamp (millisecond precision), and vehicle position, among others. Data points were collected at 60 Hz, i.e., during the experiment, a data point was generated every 0.0166 seconds.

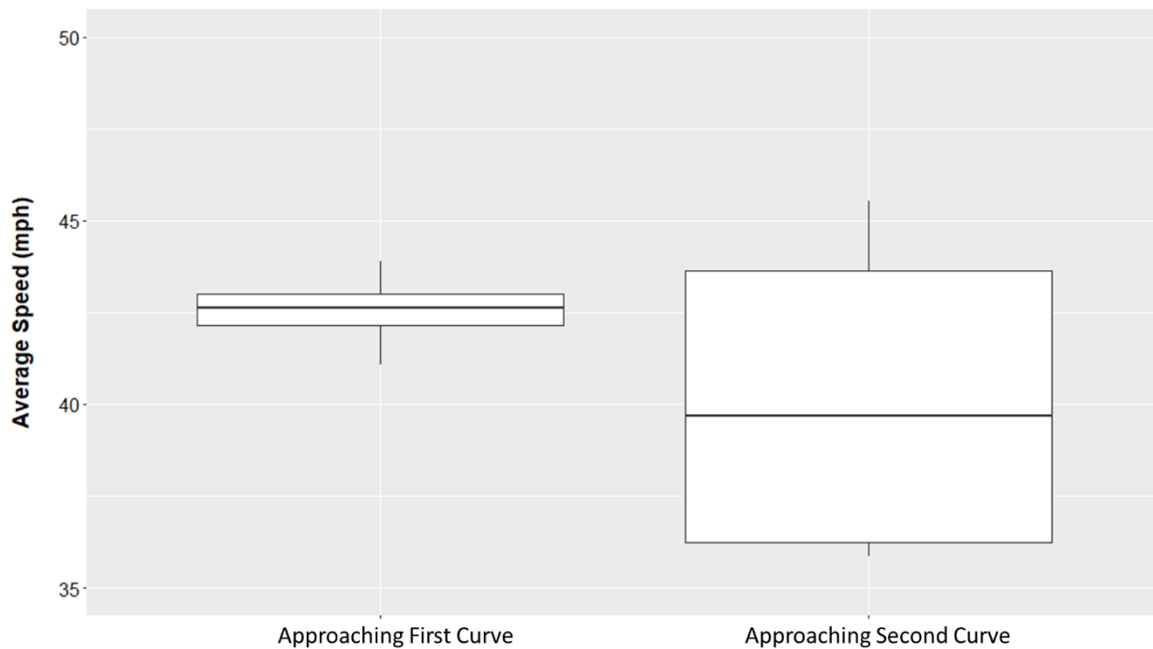
### **5.3 Data Collected and Results: Approach Speed on Curves**

Data files from the experiment were analyzed using scripts created in the R programming language. To narrow the data included in the analysis, analysis zones were defined based on the geometry of the scenario. The analysis zones defined allow the identification of points within the entire dataset associated with specific areas. Analysis zones were defined upstream and downstream of the curves shown in Figure 5.1. In the figure, Zone 4e is located 100 ft upstream of the start of the first curve, while Zone 3e is located 100 ft upstream of the start of the second curve.

Using the analysis scripts and the data identified for the individual analysis zones, speed measurements upstream and downstream of the first and second curves were

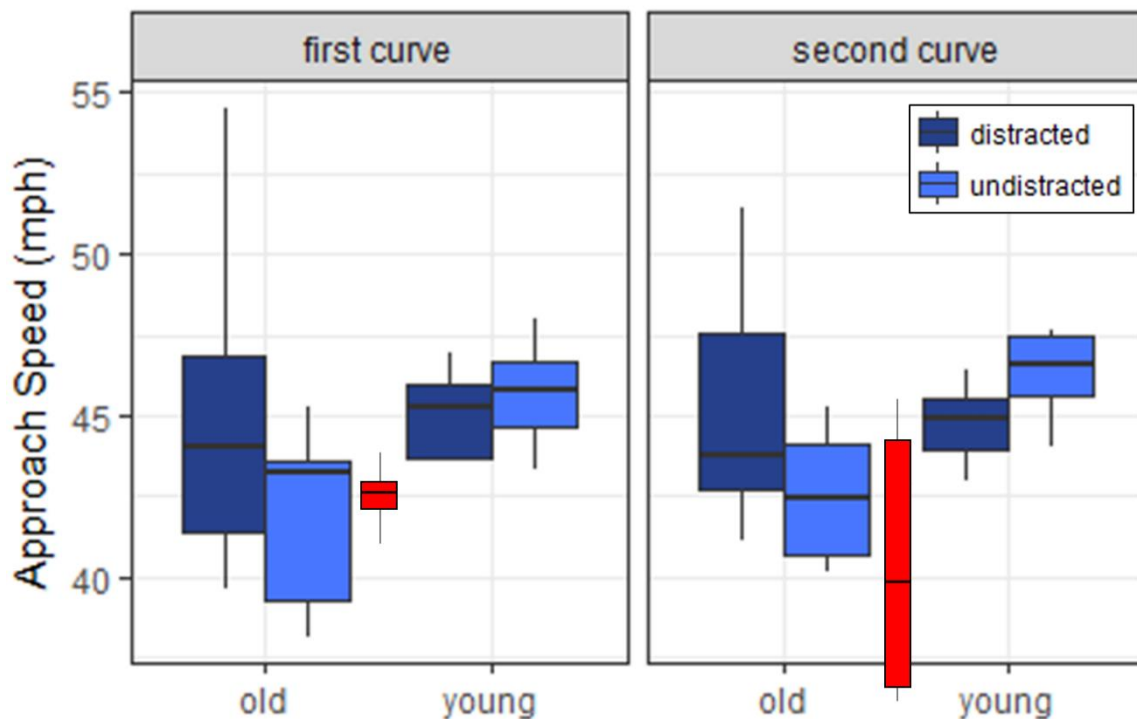


generated for each subject. Figure 5.4 shows a box plot summarizing speed observations upstream of each curve analyzed. As previously mentioned, speed values upstream of curves provide a direct comparison with the speed values obtained in the NADS experiment.



**Figure 5.4 Summary of Speed Results Upstream of Curves**

Each analysis zone associated with the plot shown in Figure 5.4 covers approximately 5 meters along the lane traveled by the subject. Therefore, speed measurements reported by zone represent the average of speed values associated with each observation within the zone. Due to the short distance covered by the zone, average speeds can be treated as an instantaneous speed measurement. A side-by-side comparison of the UW-Madison pilot experiment speed results with the results from the NADS experiment is shown in Figure 5.5. In the figure, the “upstream of curve” speed observations found via the UW-Madison pilot experiment are shown in red overlaid on the NADS data.



**Figure 5.5 Comparison of Results Between UW-Madison and NADS Experiment**

Due to the limited number of subjects included in the UW-Madison pilot experiment as well as the lack of a distraction task, a comparison of sub-scenarios is not possible. However, a general and qualitative comparison of speeds such as the one shown in Figure 5.5 is possible. As the figure shows, speed results found via the UW-Madison pilot experiment are within the range of speeds reported in the NADS experiment. The apparent stable nature of speed observations on a SHRP2-derived curve geometry across multiple simulators suggests the possibility of augmenting naturalistic driving data in the future with results from simulator experiments.

It should be noted that data from the UW-Madison pilot experiment shown in Figure 5.5 includes data from subjects who were exposed to the scenario with the stop sign as well as the one without the stop sign. In fact, when subjects exposed to the scenario without a stop sign are included in the dataset, a slight decrease in the overall speeds is observed. Since only two out of eight subjects were exposed to the scenario due to the pilot nature of the experiment, no quantification of the effects is presented.

## 6 Discussion and Conclusions

The objective of this project was to develop a driving simulator scenario from a real-world location where naturalistic data were collected. Leveraging previous SAFER-Sim research, we were able to build upon an approach to developing driving simulator scenarios from naturalistic data sets. This process enabled the research team to recreate a set of two heavily traveled rural curves present in the SHRP2 data set, where Hallmark and colleagues (2014) previously coded driver behavior.

The resulting simulator tile was integrated into a larger virtual world in the NADS-1 high-fidelity driving simulator. Using the simulator scenario that included the naturalistic curve tile, we collected behavioral data from a large sample of younger and older drivers, with and without distraction. Both driver age and secondary task interactions significantly influenced driver behavior in the naturalistic curves. Overall, these results were consistent with previous age and divided attention research (e.g., Strayer & Drew, 2004). A pilot experiment using a tile containing the same geometry was conducted at the UW-Madison full-scale driving simulator running on the RTI platform. Results, from the perspective of how drivers approach curves, were similar to those produced in the NADS environment.

This data collection highlights the possible applications of the approach to simulator tile development. Naturalistic driving studies provide just a single snapshot into a crash or near-crash event. By bringing the naturalistic roadway into the driving simulator, we may evaluate a large sample of drivers with varying task demands all in the same environment or specific situation. This essentially allows experimental research to be conducted in the same naturalistic settings where the initial research questions were formed.

The results of the simulator study suggest at least a fair amount of coherence between behavior in the simulator and on-road settings. The simulator results were

generally in line with those reported by Hallmark and colleagues (2014), with respect to changes in behavior observed with both distraction and driver age. A full validation of the simulator tile against real-world behavior was beyond the scope of this study, particularly given the costs and time associated with manual reduction of the naturalistic data.

Future research is therefore needed to investigate what, if any, differences exist between behavior in the simulator and on the real roadway and how experimenters might best address those questions in simulator experiments.

Another open question is the extent to which the ambient environment surrounding the roadway, including features like trees, houses, and signs, must match the real world to engender similar behavior. The approach taken in this study was to replicate as many of the visual features (visible from the roadway) as possible, resulting in a time-intensive process. For future work, it would be important to understand the minimal amount of features needed to yield naturalistic driving behavior. Finally, future work should also attempt to automate the tile creation process, to the extent possible, in order to reduce overall project timelines and to quickly evaluate specific sets of roadways and conditions.

Overall, the project achieved the objective of developing and testing a process of creating simulator scenarios from naturalistic driving data. One general important takeaway from these results is the breadth and detail of measures that can be extracted from the simulator relative to naturalistic data collection. This approach holds the promise of meshing the worlds of naturalistic data collection and driving simulator experiments. Future research will be able to revise and expand the capabilities and efficiency of the process, allowing this method to be utilized by transportation researchers to answer important research questions.

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