Simulation and Rapid Prototyping to Support the Deployment of Advanced Crash Avoidance Systems

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ABSTRACT

U.S. Highway 191 in southwestern Montana has been identified as the location of a number of accident clusters. The accident rate is not significantly greater than that for similar highways with similar traffic densities but the accidents that do happen tend to receive great visibility. Because of the roadway geometry and the lack of practical alternative routes, crashes and incidents in this area have a disproportionate impact on transportation in this heavily traveled corridor.

A rapid prototyping approach is being used in the driving simulation laboratory at the Western Transportation Institute (WTI) to simulate approximately 22 miles of U.S. 191 between the Big Sky Resort community and the northern mouth of the Gallatin Canyon. The simulations are used to help the Montana Department of Transportation (MDT) develop and refine safety countermeasures for that roadway. Custom roadway tiles for the simulation were designed and programmed from MDT's "as built" plans for the highway, topographic maps, and video taken from a vehicle driving the route.

Projected safety-related system deployments such as dynamic message signs and revised delineation can be electronically simulated on a geo-typical roadway. MDT engineers can "drive the roadway" to examine the impacts of prototype deployments. A sample of drivers can drive the scenarios to test the effectiveness of deployments. If changes in the systems are suggested, the simulation can be easily altered to represent the new specifications and the refinements.

The primary benefit of the visualization and rapid prototyping approach using interactive, immersive simulators is that it provides an opportunity for formative evaluation, allowing engineers to refine the design at an early stage in the system development process before significant resources are invested in the deployment. The proposed system hardware and operations are all produced by computer graphics for a very small fraction of the cost of the actual deployment. Changes at this point may involve only a "click and drag" operation on a computer interface, changing one image for another, switching JPEG images of signs, or selecting alternative commands. By evaluating and refining the deployment early in the process, considerable time and money can be saved if changes need to be made to achieve the desired traffic objectives.

BACKGROUND

We joined the stream of traffic heading south, the Gallatin River alongside and usually much below the roadway, a dashing high-gradient river with anglers in reflective stillness at the edges of its pools and bright rafts full of delighted tourists in flotation jackets and crash helmets sweeping through its white water. Gradually, the mountains pressed in on all this humanity and I found myself trailing a cattle truck at well below the speed limit. This combination of cumbersome commercial traffic and impatient private cars was a lethal mixture that kept our canyon in the papers, as it regularly spat out corpses. In my rearview mirror I could see a line behind me that was just as long as the one ahead, stretching back, thinning, and vanishing around a green bend. There was no passing lane for several miles. A single amorous elk could have turned us all into twisted, smoking metal.

Thomas McGuane, Gallatin Canyon Stories, 2006

U.S. 191 in Southwestern Montana is the primary route to the west entrance of Yellowstone National Park as well as a major transportation corridor between Montana and Idaho. The 25-mile Gallatin Canyon section of U.S. 191 between

Bozeman and Big Sky is a scenic mountain highway characterized by frequent sharp curves and a narrow right-of-way constrained by canyon walls and a major river. A large percentage of drivers are unfamiliar with the highway and with safe driving speeds at given locations and under different weather conditions. Accidents are frequently attributed to distracted drivers watching wildlife, whitewater rafters, or the scenery. Alcohol-fueled aggressive driving is also a significant safety factor.

Traffic flow is marked by a significant speed variance with limited opportunities for passing slow-moving trucks and recreational vehicles. Development of the community and ski resort of Big Sky has greatly increased traffic with significant numbers of trucks carrying building supplies and carloads of construction and service workers moving between Bozeman and Big Sky. Weather and road conditions are unpredictable and frequently include ice on bridges and in shaded areas. Drivers unfamiliar with the road may exceed safe speeds in the short radius curves. Projections suggest that the traffic and safety challenges will only worsen in the future years due to continued development of a major residential and business area adjacent to Big Sky. Figure 1 shows an aerial photo of the whole Gallatin Canyon area north of Big Sky including U.S. 191 and the surrounding terrain. Figures 2 and 3 show specific areas of the highway.

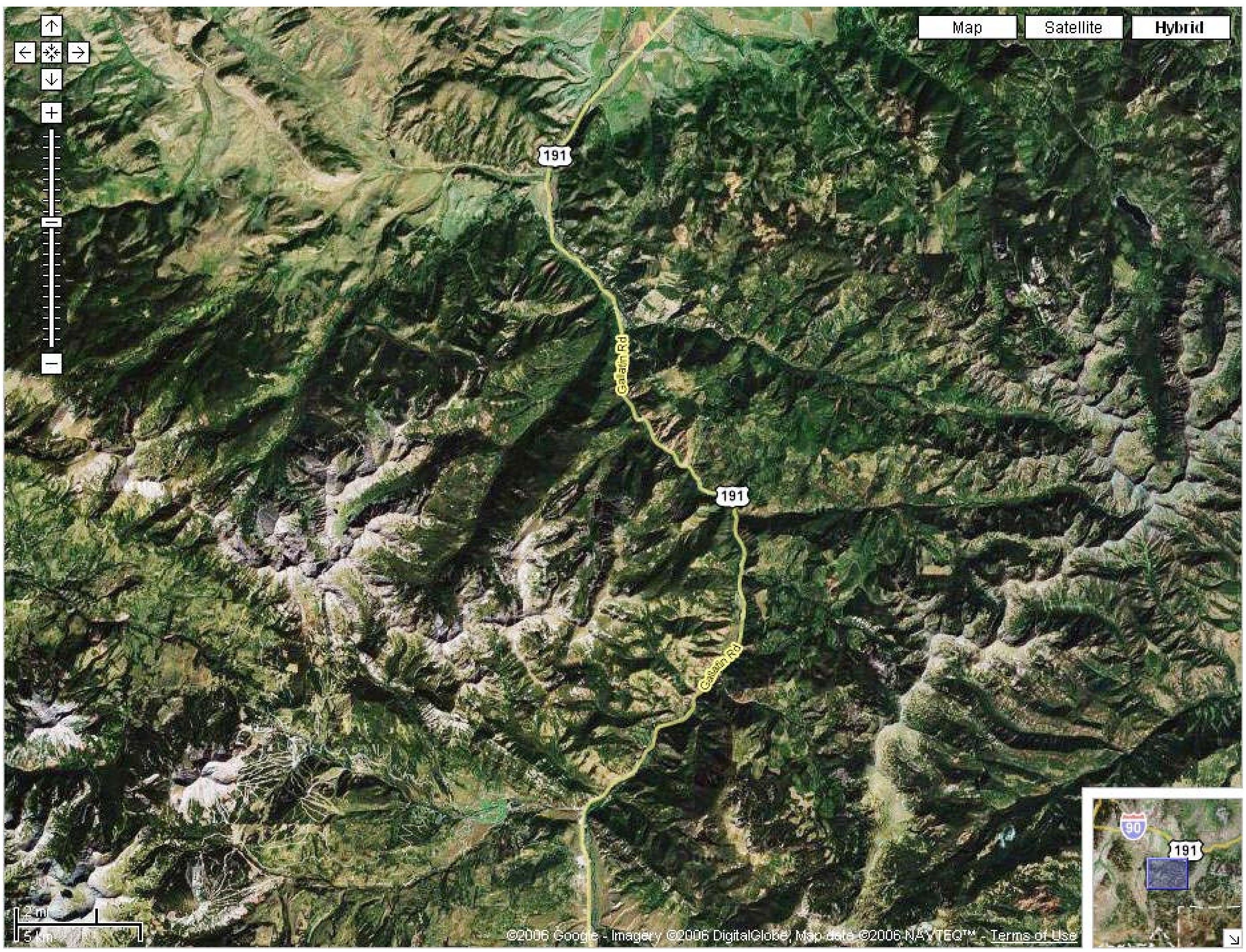

Figure 1. The Gallatin Canyon Area (courtesy Google Imagery)

Figure 2. A 35 MPH Bridge over Gallatin River (courtesy Google Imagery)

Figure 3. Typical Roadway Section (courtesy Google Imagery)

Most of the roadway is posted with a 60 MPH speed limit but with advisory speeds of 45 MPH and even 35 MPH in some of the areas with short radius curves and limited sight distance. Enforcement of safe driving speeds is a challenge. Because of the nature of the roadway, there are few areas in which law enforcement officers can stop to clock traffic speeds or to pull over and ticket violators. The use of photographic speed enforcement has been discussed but it would require legislative action and there is little evidence of its long-term effectiveness in controlling speeds. Voluntary compliance with safe speeds for existing driving conditions becomes a key.

THE CHALLENGE

A number of high-profile accidents have suggested the need for improved travel advisories and warning information for drivers to reinforce the voluntary compliance. Curve speed warning systems, variable speed limits, upgraded lane delineation, and real-time road condition alerts including icy road warnings are all candidate countermeasures. The efficacy of these deployments on US 191 needs to be tested before expensive installations of these systems are made. The Montana Department of Transportation (MDT), supported by the Western Transportation Institute (WTI), is conducting a demonstration project in which potential Intelligent Transportation System (ITS) deployments are tested using an immersive simulation of the roadway in the WTI Driving Simulation Laboratory. Engineers, as well as representatives of the driving public, will be able to drive the simulated US 191 highway to experience and evaluate prototype deployments. Detailed measures of driver performance are made to characterize any resulting changes in driving behavior.

THE WTI SIMULATION LABORATORY

WTI's Driving Simulation Laboratory is centered on a DriveSafety 500C fixed base simulator in a light and sound controlled 35 square meter room. An adjacent office is used for subject reception and briefing and data analysis. Adjacent to these rooms is a 100 square meter room designed to house a future motion-based multi-cab simulator.

The DriveSafety simulator cab is a quarter of a 1996 Saturn SL sedan with fully functional controls. An array of five rear projection plasma displays is arranged in a semicircle around the front of the cab providing a 160-degree horizontal field of view. Rear-view mirrors are simulated on the displays. The simulator has 3-D auditory displays using five speakers including a "seat shaker" subwoofer attached beneath the driver's seat. Vehicle dynamics and control responses are physics-based. The system currently runs on Vection and HyperDrive 1.9.35 simulation software using a network of six simulation computers and a dedicated data collection and analysis computer. Figure 4 is an artist's conception of the simulator.

Figure 4. Artist’s conception of the driving simulator.

Roadway geometries, markings, and traffic control devices are consistent with standard traffic engineering practices. The researcher may select from numerous roadway geometries including rural and urban freeway, city streets, paved rural roads, or unpaved rural roads. Traffic control devices such as signals, regulatory and advisory signs, barriers, delineators, and work zone controls may be placed in the scenarios. Pedestrians may be shown standing, walking along the roadway, or crossing the roadway in programmed paths. Ambient traffic density may be set at desired levels and particular makes and models of vehicles may be selected including passenger cars, delivery trucks, motorcycles and other vehicles. The ambient vehicles drive autonomously, obeying all traffic rules unless they are programmed for an abnormal or illegal maneuver (e.g., speeding or running a red light.)   Scenarios may select day or night driving. The nighttime condition replicates a partially moonlit night with limited scotopic visibility and many visible stars. Weather conditions may be simulated to include rain, snow, wind, ice, or fog in the scenario.

DRIVING SIMULATOR “WORLD” AND SCENARIOS

Developing testing scenarios on the WTI Driving Simulation Laboratory is a straightforward task. Using the Hyperdrive 1.9.35 software system, users can define terrain, roadway types, and scenario entities from a set of standard menus. First the roadways, environmental conditions (e.g., daytime/nighttime, weather, coefficient of friction), traffic conditions, and natural and cultural features for the desired scenario are determined. Tiles representing the appropriate roadway and terrain features are selected and assembled end-to-end to create the simulation “world”.   The programmer then selects from a library of buildings, vegetation, vehicles, pedestrians, animals and other such static and dynamic entities. These are inserted onto the tiles using a “drag and drop” process. For moving entities, “triggers” defining the initiating condition and the speed and path of the object are entered. Environmental conditions (e.g., snow, rain, fog, decreased road friction) are entered. Performance measures (up to 48 measures) for data collection purposes are then selected.

Using the generic tiles supplied to all purchasers, the user can create a roadway containing many of the specific features needed for testing. For example, WTI created a representation of the I-90 roadway over Bozeman Pass to test the effects of alternative animal warning signs on vehicle speed and driver alertness (Stanley, Lassacher and Hardy, 2006). Tiles representing approximately 20 miles of a divided highway with Jersey barriers in the median were placed in a generic hilly rural terrain. In one location, a “road kill” was placed to suggest the presence of animals. Custom signs representing alternative warning signs were developed and placed on the scenario “world”. Near the end of the scenario, a group of deer was triggered to wander onto the roadway. Effectiveness of the alternative signs was evaluated by changes in driver speed and distance from the obstacles when the brakes were actuated.

Existing tiles delivered with HyperDrive represent generic terrain with relatively flat urban terrain, freeway terrain, and slightly hilly rural terrain. Where the generic terrain is not an adequate representation of the planned driving environment, a custom simulator world of specially programmed tiles may be obtained. As an example, Slick, et al. (2006) used custom tiles representing the streets of Manhattan, Kansas, for a study of the efficacy of driver training in the simulator versus training in an actual vehicle. The custom world duplicated the in-vehicle driving training environment of the streets of that city to ensure that both groups were trained in identical environments.

Safety countermeasures are among the dozens of traffic control entities that may be inserted by click and drag menu selections from the standard simulation menus. Installing a dynamic message sign (DMS) over a roadway, for example, requires inserting the DMS “bridge” to support the sign, selecting and placing the sign board on the bridge structure, and selection of the sign content, layout, and letter fonts. Messages are typed onto the sign screens. Messages requiring multiple screens may be selected in the same way. The entire process requires only a few minutes.

THE GALLATIN CANYON SIMULATION

An analysis of serious accidents on US 191 identified accident clusters near Mileposts 52 and 66 in the Gallatin Canyon. Another accident cluster was identified north of the canyon mouth near the community of Gallatin Gateway at milepost 77. With guidance from MDT, it was decided to concentrate efforts on areas within the canyon, itself, for simulation and visualization studies.

The manufacturer of the simulation system, DriveSafety, Inc., developed a series of six custom tiles representing the highway and terrain of US 191 through Gallatin Canyon between milepost 48 and milepost 70. To develop this simulation, DVD footage of the roadway was recorded and sent to the simulator manufacturer. In addition, the engineering road drawings for typical horizontal curve profiles, and GPS data for each mile marker (north and southbound) along the segment of roadway of interest were supplied. The manufacturer’s tile designer also employed the USGS mapping information. The GPS data was not used as the measured latitude/longitude data did not register accurately with the latitude/longitude coordinates in the USGS mapping system. The designer used MultiGen Creator Pro and Adobe Photoshop software to generate the visual database. Additional proprietary software was employed by the manufacturer to generate the additional datasets required for the real-time system. The visualization included the two-lane highway bordered by mountains and a river. Both sides of the right-of-way were forested and guard rails were placed along the road as it curved next to the river. The two bridges over the river were protected by concrete

Figure 5. Entering 35 MPH Bridge (Actual)

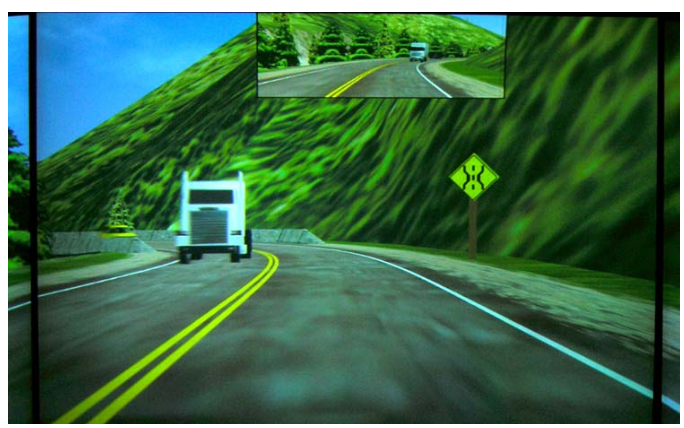

Figure 6. Entering 35 MPH Bridge (Visualization)

barriers. The visual simulation prepared by DriveSafety did not include cultural features such as buildings and fences. These were added in the appropriate locations using the HyperDrive data base of simulation entities. A custom guardrail entity was made available to allow placement of additional guardrails by click-and-drag operation. In some areas, trees were also added to the tiles to more closely resemble the heavily forested roadsides. One necessary departure from the real world roadway was that the rural buildings and fences on the generic simulation entities menu are of typical design for a rural Midwestern landscape. In the real-world environment of US 191, a much greater use of rustic materials such as logs and rock are used in building.

Programming of realistic ambient traffic provided a challenge to the scenario fidelity. US 191 experiences large time-of-day and day-of-week variances in traffic type and density. For our testing, we developed several different versions of the traffic scenarios including one with no same-direction traffic, one with relatively light same-direction traffic traveling approximately at the speed limit, and one with a significant number of slow-moving delivery trucks that would create backups of vehicles and passing attempts where passing was allowed. Figure 5 is a photograph of the US 191 roadway and Figure 6 is the simulation of that same area. Figure 7 is a visualization of a DMS sign.

Figure 7. Simulated DMS Sign.

PRELIMINARY RESULTS

For an initial study, WTI was requested to evaluate the effects of variable speed limits posted on DMS signs on driver behavior and safety. A pilot series of speed studies was conducted using the simulation. These studies were conducted using clear weather, dry roads, and a minimum of ambient traffic. Drivers were first trained on driving the simulator and then drove the simulated 22 mile roadway with one intermediate stop at the halfway point. Speeds were tested with no posted speed limits, speeds posted at a 60 MPH limit on a DMS on a bridge over the road, and speeds posted at 50 MPH on a DMS bridge over the road. Speeds were measured at each milepost. The roadway geometry at the measurement point was categorized as straight, curving, entering a curve, or exiting a curve.

Because of differences in measurement methods between the simulator and the real-world driving environment, it is not possible to directly compare the simulation with the real world. Speeds measured in the simulator with no posted speed limits and with 60 MPH limits posted on DMS signs were very close to those reported and experienced on the actual roadway (see Figures 8 and 9). There was little difference between the speed profiles (mean and 85^{th} percentile speeds) between the posted 60 MPH limit and with no posted limit. With the posted 50 MPH limit, speeds remained the same in the curves but were approximately 6 MPH slower in the straight sections than with more permissive limits.

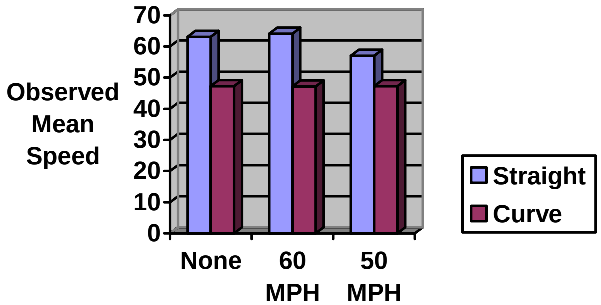

Figure 8. Effect of
Posted Speed Limit

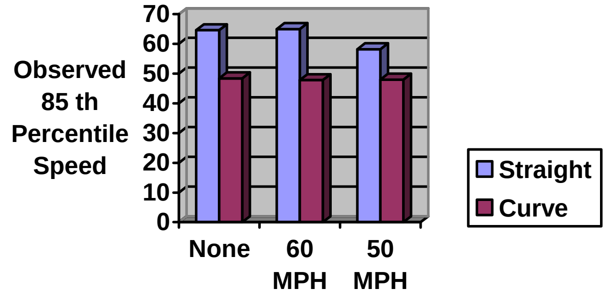

Figure 9. Effect of
Posted Speed Limit

LESSONS LEARNED

The Gallatin Canyon project was a small project to explore the simulation/visualization technology application of a medium fidelity immersive driving simulator for evaluating driver responses to advanced crash avoidance systems on a rural highway. In the future, additional crash avoidance systems may be explored. There is interest among several agencies in a simulation test of lighted centerline delineation to make the roadway more visible in inclement weather. Delineator lights have been developed as simulator entities and are available for testing. A lane departure warning system simulating virtual shoulder and centerline rumble strips has been developed and tested on a generic terrain for a different project and would be available for testing on a specific roadway such as US 191.

WTI has begun the process of obtaining a second, higher fidelity driving simulator that could be used to support visualization and simulation studies. Many of the lessons we have learned in this initial study are guiding the requirements for our next-generation driving simulator. Some of these lessons are described below.

Simulator Adaptation Syndrome

Simulator adaptation syndrome (SAS) or, more commonly, simulator sickness is always an issue when using an immersive driving simulator (c.f., Mollenhauer, 2004). This syndrome may include dizziness, headache, or abdominal discomfort while in the presence of the moving visual scenes. As part of our studies, we routinely screen the drivers for these symptoms both before and after testing. During our earlier studies, we found that approximately 10 percent of our drivers reported increased levels of these symptoms after a drive. The frequency and intensity of SAS appears to be greater in female drivers and to increase with age.

We have identified several procedures for minimizing SAS, including (1) prescreening drivers for medical histories of motion sickness, migraine headaches or other predisposing factors, (2) presenting a carefully designed program of pretraining to acclimate the drivers to the simulator, (3) using testing scenarios of no more than 15 minutes in length, and (4) maintaining a minimum level of ambient lighting in the simulator room to prevent the driver from becoming totally immersed in the simulation.

Driver Sampling

While age and gender differences in susceptibility to SAS create challenges in driver selection, it is crucial that a representative sample of drivers be tested. For convenience, many research centers recruit a standard subject pool of university freshmen for simulation testing. We have found that younger drivers perform differently than drivers above, say, 30 years of age. Younger drivers score much higher on tests of perceptual and cognitive skills related to driving. As in the real world, though, younger subjects tend to take more risks and have more crashes than older drivers. In order to generalize results to the driving population, simulation testing must sample from the entire range of drivers.

DMS Sign Messages

Some issues arose in the development of messages to be displayed on the DMS signs. In the WTI system, message content is entered as free text so the user must be familiar with any conventions for message content and structure. For the development of messages for the simulator, widely accepted standard guidelines (e.g., Dudek, 2004) should be consulted and observed. In addition, several states have developed message content guidelines for DMS but there are some differences in practice between jurisdictions. Appropriate local guidelines for the roadway segment should be identified, where available, and should guide the format and content of messages displayed in the simulator.

Tile Limitations

The proprietary software used to develop the simulation could not easily simulate elements of the near-vertical rock faces that appear in some areas of the canyon due to limitations in the slope and distance of the terrain. Terrain tiles representing higher and steeper mountains were available and could have been added adjacent to tiles containing the roadway to provide a view of distant mountains but, because of the many short radius curves in the roadway, it would have been impractical to place these next to the roadway.

One issue of driving in terrain with mountains and trees is the influence of sunny versus shady areas. In the real world, shady areas are more likely to have icy or wet roadways providing reduced road friction. The alternating areas of light and darkness also affect the driver's vision and may hide an obstacle, or even a curve, in the deeper shadows. The current WTI simulator does not have a capability to simulate shadows. A future simulator will have this capability.

The tiles developed by the manufacturer displayed guardrails in most of the appropriate areas along the highway. A few areas lacked guardrails that needed to be added to the simulation. A guardrail entity was included with the available scenario entities but it was overly cumbersome and time-consuming to use. It required the user to roughly place the guardrail section and then gradually slide the ends into a more accurate alignment with adjoining rails. For barriers with any degree of thickness (e.g., Jersey barriers) alignment of the straight barrier sections on a curving roadway geometry was a particular challenge. Alternative methods of adding such roadside barriers need to be explored, especially including a friendlier user interface.

Contracted Versus In-house Tile and Entity Development

A major advantage of visualization and rapid prototyping is that it can be done quickly. Working with the simulator manufacturer to develop custom tiles can become a time-consuming process involving negotiation of contracts and fitting the scenario development time into the manufacturer's schedule. Revisions and corrections to the tiles may require several iterations of this process. Such lengthy and complex interactions with the manufacturer can reduce the overall efficiency of the prototyping process. WTI is exploring ways to shorten this process including obtaining an ability to develop the custom tiles in-house through greater access to the proprietary code used for development or through use of alternative software that makes the tile development and revision features available to the user.

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