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Audio-Visual System Design Recommendations from Experience with the UMTRI Driving Simulator

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ABSTRACT

Sometimes simulator designers are so enamored of the technology to create detailed road scenes that they lose sight of the goals that guide simulator design, with usability and usefulness suffering as a result. The third generation UMTRI Driving Simulator was designed with 4 goals in mind: (1) facilitate running experiments, (2) support demonstrations, (3) facilitate configuration verification and troubleshooting, and (4) provide high quality audio and video signals. The time spent on demonstrations (to sponsors, the public, and the media) can equal the time testing subjects and the impact of those demonstrations can be significant. Further, the time spent troubleshooting equipment, especially the cameras, cables, amplifiers, etc. associated with the audiovisual system can far exceed the time spent on demonstrations and testing subjects.

This paper lists 30 recommendations for designing a simulator audiovisual system. For many recommendations, specific model numbers or web sites are provided. Noteworthy recommendations in support of the testing and demonstration goals (1 and 2) concern (a) the camera locations to consider (face, screen, interior, feet), (b) hiding cameras (yes, using lipstick cameras), (c) monitoring of the experiment (the operator should see everything), (d) audio and video switching (use a one, not multiple mixers for each input and output modality), (e) assuring visitors can see and hear everything subjects see and hear, (f) accommodating TV crews, (g) light control (use black carpet), and (h) power (provide UPS for all critical items). To facilitate troubleshooting (goal 3), label and diagram everything, use geared tripod heads to aim the LCD projectors, and provide access to the front and back of all equipment. Finally, to assure signal quality (goal 4), use broadcast quality components, especially shielded cable, and double check all hand made cables.

Although many of the recommendations may seem obvious in hindsight, many were not thought of during planning of a new simulator by a team with considerable experience with using and developing driving simulators. Users of existing simulators and those building new simulators should benefit from the recommendations in this paper.

INTRODUCTION

Unpredictable weather and road conditions during the winter months make collecting on-the-road driving data in Michigan and other northern states challenging. Fortunately, developments in low-cost computing over the last decade have made driving simulator evaluations a viable alternative. Furthermore, it has been apparent for some time that advanced technology found in aircraft and computer systems would eventually be found in motor vehicles (reference 1), but for reasons of safety, concepts would initially have to be evaluated using driving simulators. This paper provides design recommendations for a simulator audiovisual system based on experience in developing and implementing driving simulators at UMTRI, especially the third-generation simulator.

The First-Generation UMTRI Simulator

In the early 1980s, the first author's limited research funds were used to purchase a Commodore 64 with a cassette drive. A discarded TV served as the monitor. A high school student wrote a computer program for the 64 that showed pairs of solid rectangles simulating reflective road edge markings. With the sum of 3 nonharmonic sinusoids as input, a curving road at night was simulated (Figure 1). An UMTRI technician connected a potentiometer to a steering wheel, providing the rudiments of a "driving simulator" used in several experiments (reference 2). The task was attention grabbing, but the performance of drivers was not very realistic as lane departures were common and substantial, primarily because there were no consequences of a departure as in real driving. On the positive site, the simulator was portable, and 2 were built at UMTRI.

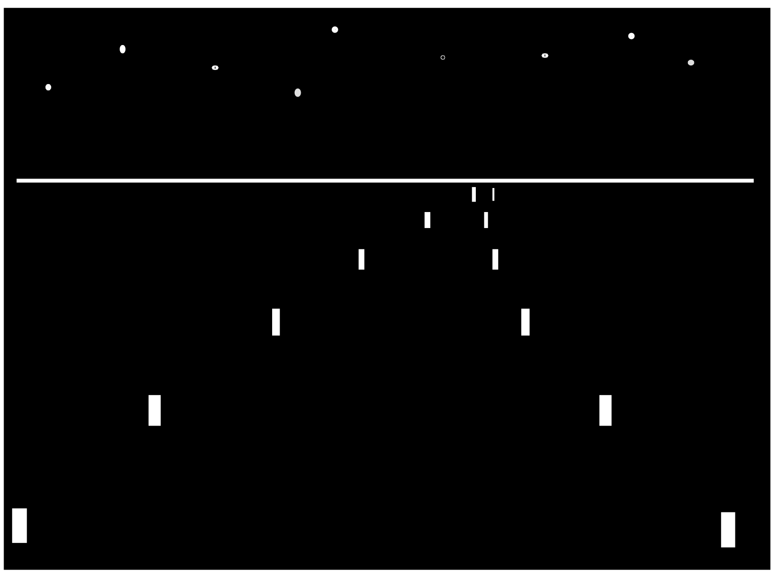

FIGURE 1 Sample night driving scene from the First Generation Simulator

The Second-Generation UMTRI Simulator

As the result of an UMTRI retreat, $50,000 was set aside for the purchase of a better simulator. The purchase of an STI PC-based simulator (http://www.systemstech.com/stidrsm1.htm) was contemplated, but the investigating team thought that better graphics could be developed on the Macintosh platform, so they did (reference 3). Silicon Graphic computers, the standard platform for simulation at that time, were far too expensive.

That second-generation simulator (Figures 2 and 3) was used for about 20 experiments on in-vehicle devices, driver workload, and other topics (e.g., references 4, 5, 6, 7, 8, 9, 10). Over time, the simulator evolved from a single computer to a networked architecture where various tasks (scene graphics, sound, simulation of traffic, etc.) were distributed between computers to overcome the computational limitations and to provide implementation flexibility. The most recent version of the simulator provides torque motor feedback, speed-specific sound, and scriptable

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traffic. Roads could have curves but there are no intersections. The simulator was reasonably easy to use and everyone on the research team had a copy, allowing them to develop and test scenarios and worlds in their offices (using a mouse as the input device), minimizing the demand for simulator time and scheduling conflicts.

FIGURE 2 Sample scene (left) and setup (right) of the second-generation simulator.

To discourage drivers from leaving the lane, an important feature of the second-generation simulator was emulating the steering wheel torque from a tire dropping off of the pavement edge and the steering wheel shake from off-road driving (with the appropriate sound of driving over gravel).

The Third-Generation (Current) Simulator

The start up package for the current UMTRI Director included $100,000 for a new driving simulator. After identifying the research needs of the investigators who might use the simulator and considering alternatives, a DriveSafety simulator (http://www.drivesafety.com, formerly Hyperion Technologies, KQ Corporation, and GlobalSim) was purchased. The total cost for the computers, software, 4-channel/4 LCD projector system, room modifications, supporting hardware, and billed staff time was at least $250,000. Currently, about 10 other universities and suppliers have simulators from this vendor, with the number of visual channels varying from site to site. Quite frankly, simulation technology has advanced to the point where human research specialists can focus on their expertise on research, not simulator development.

The third-generation simulator (Figures 3, 4, and 5) includes (a) the vehicle cab from the second-generation simulator, (b) 120 degree forward and 40 degree rear fields of view (c) 4-channel speaker systems to provide directional sound, and (d) 8 computers to generate scenes, simulate in-vehicle controls and displays, and control the simulation. The cab has operating foot controls, a steering wheel connected to a torque motor for force feedback, a back-projected, computer-generated speedometer/tachometer cluster, a center console touch screen, a driver's seat with 8 vibrators for haptic feedback, and wheeled, removable hood and rear sections. The simulator can present the off-road sounds from the second-generation simulator, but not the off-road torque feedback, at least not yet.

The simulator facility has a control room and a curtain-enclosed shop area. A facility feature is the large eye to screen distance (approximately 15.5 feet, 4.7 m, depending on the seat position) so interior-exterior accommodation resembles real world behavior. This is less than the ideal 20 feet (6.1 m) in the second-generation simulator, a compromise due to a lack of space. Both the second-and third-generation simulators are unique in having a back-projected instrument cluster and a center console touch screen, hardware (and software) desired for driver interface evaluations. The prototyping of driver interfaces will be covered in a future paper.

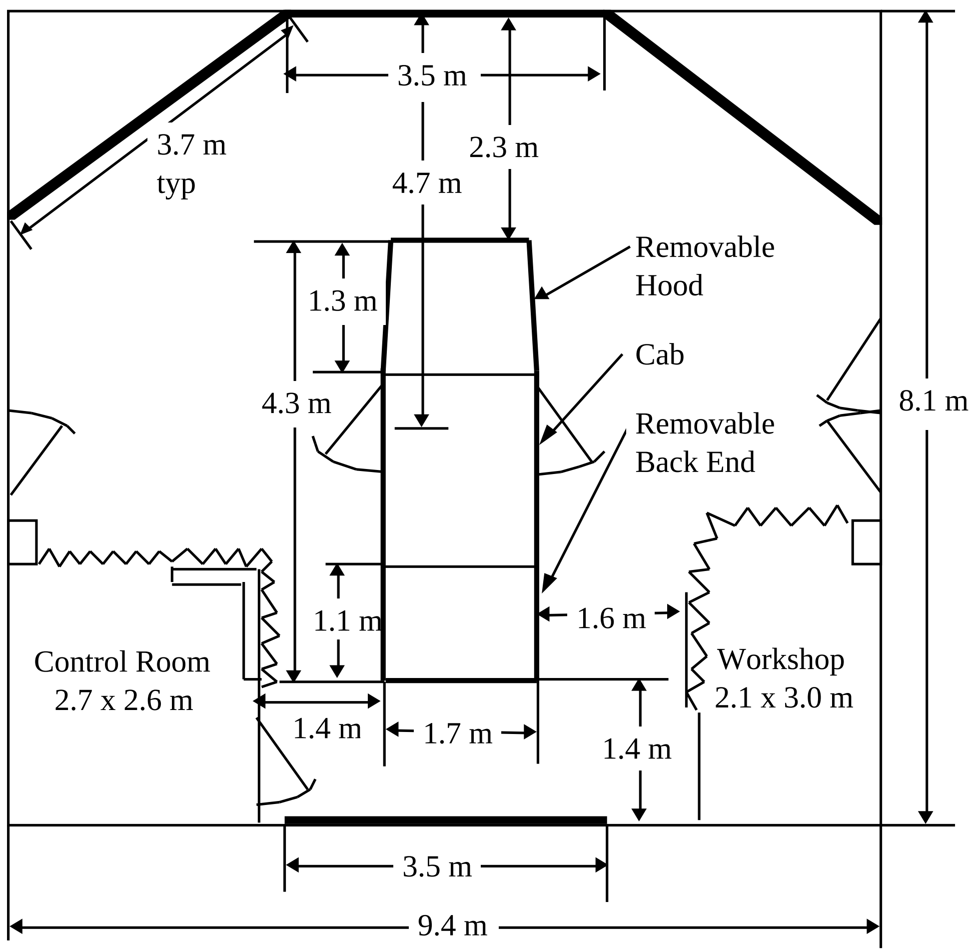

FIGURE 3 Simulator Facility Drawing.

The simulator is designed so subjects can only see the cab interior and the road scene from the driver's seat. Everything else in the lab is either covered with black material or is behind closed curtains. The control room is conveniently located next to the entry door so experimenters do not need to cross the simulator bay to access the control room. Ideally, the control room would have been truly separate, with its own entrance so subjects cannot see the control room equipment as they enter (now only blocked by curtains). The control room is located in the corner behind and to the left of the vehicle. The control room is outside the field of view of the driver yet close enough so the simulator operator can directly communicate with the subject if the speaker system is not working.

FIGURE 4 Road Scene as Presented by Three Forward Channels

FIGURE 5 Simulator Control Room and Forward Scene (Single Channel)

WHY THIS PAPER WAS WRITTEN

The more than a decade of experience with driving simulators has provided the UMTRI staff with knowledge of how driving simulators should be built to be easy to use and useful for human factors research. Given that many others are developing simulators but lack that experience, sharing UMTRI's knowledge makes sense. That knowledge is summarized in recommendations that follow, only some of which were identified before development of the third-generation simulator began and many of which emerged with clarity when this paper was written. These recommendations will be most useful to those designing midlevel to high-end driving simulator facilities, though they should also be useful to those designing less sophisticated facilities. UMTRI's approach was to incorporate unique features into the audio-visual system to distinguish the UMTRI implementation from other off-the-shelf simulators using the same image generators and scenario software.

The design recommendations relate to 4 goals: (1) facilitate running experiments, (2) support demonstrations, (3) facilitate configuration verification and troubleshooting, and (4) provide high quality audio and video signals.

GOAL 1: FACILITATE RUNNING EXPERIMENTS.

Recommendation 1. Provide quad video to show what subjects do.

In driving simulator experiments, measurements of driving performance (steering wheel angle, speed, etc.) are collected and subjects are videotaped as they drive. Outtakes from those videotapes are more effective and vivid in communicating what occurred in an experiment than pages of printed text or long explanations. Furthermore, it is extremely important to have a video backup of digitized data.

Quad split images are typically recorded in driving studies, usually including the forward scene, the driver's face, and the vehicle interior. The forward scene shows the primary source of demand. The subject's face reflects anxiety (and difficulties with the task), shows where subjects are looking, and is an early indicator of motion discomfort, a significant issue. The interior image shows control use and may be analyzed to determine task times and the number of errors. The fourth image might be a close up of an interior component, the speedometer/tachometer cluster (to show speed), or the rear scene. Given the low cost of a quad splitter (about $200 for a color unit), cameras ($200 or less for small, high-quality color cameras with a zoom lens, http://www.supercircuits.com), and the commodity nature of VCRs and camcorders (analog or digital), quad recording should not be a financial burden to those with limited resources. With a quad splitter in hand, even low budget student efforts should be able to set up a quad system.

In the future, low-cost digital video systems will make recording more than 4 video channels cost effective. However, the rooms used for conference presentations (and projection screen sizes) are unlikely to change, and if more than 4 images are presented simultaneously, some images will be too small for some of the audience to see, defeating the purpose of showing them. This may serve as a disincentive for recording more than 4 images.

Recommendation 2. Provide more than 4 images from which to select for taping.

At UMTRI, when many experimenters are using the simulator, the experiment being conducted can change from hour to hour. If cameras need to be re-aimed for each experiment, too much time is wasted between sessions and the quality of video suffers as experimenters rush to prepare for the imminent arrival of subjects. Re-aiming can generally be avoided if enough cameras are provided. This has led to the installation of 8 cameras in the third-generation simulator including 2 face cameras (one of which is a backup in case of a failure). (See Table 1.) That total will increase when the eye tracking system is installed (a FaceLab System from SeeingMachines). (See SeeingMachines.com.) Fewer cameras could have been used if every camera had remotely controlled tilt, pan, zoom, but those mechanisms would have made the cameras too conspicuous and added considerably to the cost.

TABLE 1 Cameras Installed or to Be Installed in the UMTRI Simulator

#	Camera	Location	Comment
1	Face 1	Mounted on inside mirror at driver's face	Off angle location makes looking straight ahead odd (restate), but glances to center console are evident
2	Face 2 - tilt, pan, zoom (TPZ)	Face camera mounted above center of screen	Roof line may cut off part of subject's face, tilt-pan-zoom allows camera to be aimed at interview station next to car and room pan view
3	Foot	Behind center console aimed outward at brake & accelerator	Shows hesitation and movements between accelerator and brake. Note: label pedals to aid identification. Illuminate with IR light.
4	Over the shoulder	Mounted near center interior light	Shows operation of center console, hands on right side of steering wheel, best view of what is being operated
5	Dashboard side view	Mounted near right edge of passenger sun visor	Shows when controls are touched but not which one
6	Package shelf panorama	On package shelf aimed forward between seats	Provides combined view of interior and wide shot of screens, used when running short of channels on output quad splitter.
7	Rear TPZ	Above rear screen	Allows for room overview and seeing all front images
8	Floater	Mounted on tripod	Has large zoom. This camera is used as needed for special shots of the IP and to show remote tech support screen images or hardware close ups.

Recommendation 3. Hide the Cameras.

Typically, instrumented vehicles and driving simulators use very small cameras, sometimes referred to as lipstick or thumb cameras because of their size. These cameras should be inconspicuous to avoid distracting subjects and minimize the blocking of locations that subjects should see. Some believe cameras should be invisible, for example hidden in the vents and behind the interior mirror. Invisibility is costly, makes aiming difficult, and requires obtaining permission for covert observation from human subject review boards. In a relatively dark room, with a driving task to perform, subjects tend to ignore the presence of cameras after a few minutes.

Recommendation 4. Put a monitor or monitors in front of the operator simultaneously showing all inputs to the video system as well as what is being recorded.

These monitors are needed to identify that there is video input, which image is on each channel, that the quality is adequate, and to assist real-time switching when different images are required for different portions of the experiment. It is also important to have a monitor dedicated to the images being recorded by the VCR. Without this information, the wrong images could be recorded for an entire experiment.

In the current simulator design, all 16 primary inputs are fed to a group of 4 monitors, each of which is connected to a quad splitter. The advantage of this design is that within each group of 4 images, 1 of them could be enlarged when additional resolution is need by the viewer, for example to closely observe a subject when motion sickness is likely. A less costly design would be to have a single large monitor (say 19 inch (48 cm)) connected to a 16 image multiviewer/multirecord processor (e.g., Supercircuits QS33, http://www.supercircuits.com or TVOne VS-1610, http://www.tvone.com/). If additional flexibility in image presentation on a single display is desired, a more expensive splitter such as a Zandar DX, MX, or OmniVideo (http://www.Zandar.com) could be used.

Recommendation 5. When there are many image sources and displays, use a single switcher to simplify image routing.

Images from the 4 simulator channels, 8 cameras, 2 in-cab computers, and other sources need to be routed to a variety of places, but in particular to the video recording system (actually, the quad splitter) and sometimes the projection screens and elsewhere. Ideally, a single 24x16 switcher would have provided the desired capability, and been easiest to wire and use, but there were cost constraints. Fortunately, an 8x4 switcher was recycled from the second-generation simulator, and its output served as input to a 16x16 switcher, the main switching unit. The input-output mapping of the 8x4 switcher is not changed very often, so confusion about the source of those 4 channels on the 16x16 switcher is reduced.

The main switcher uses LEDs to show the mapping of inputs to outputs (Figure 6), an unusual design feature that greatly enhances usability, especially when the channel list is posted on the unit.

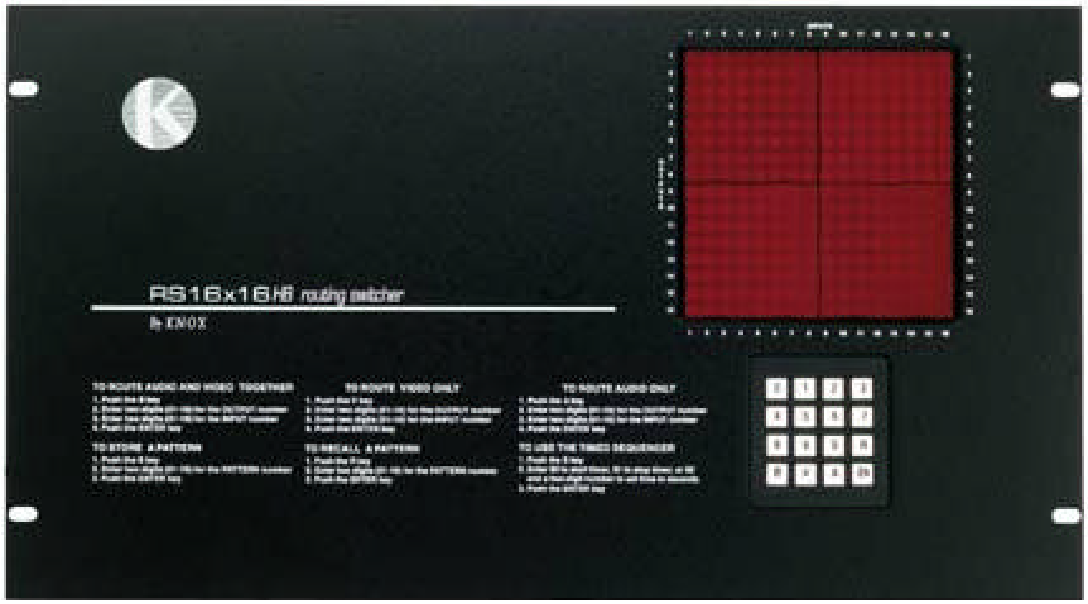

FIGURE 6 Knox RX 16x16HB Switcher Face
Source: http://www.knoxvideo.com/Products/kv_RS16x16.asp#frontview

Recommendation 6. Use a single device to control the audio output and another for the audio input.

To support studies of directional audio, 4 speaker systems were installed in the third-generation simulator. They included (a) 10 speakers in the cab from a Nissan Altima, (b) 4 speakers in the corners of the room for demos (described later), (c) 4 speakers in the control room for debugging, and (d) 5 speakers in the cab connected to the simulator for vehicle sounds. To mix sounds from several computers and send them to the appropriate speakers, a 12x4 audio mixer (Figure 7) was used. The unit selected was the best performing 4-channel mixer available in the desired price range. Unlike the video switcher, the mixer lacks a unified graphical interface and errors are easy to make. For example, to reduce a signal level to an output one can (a) reduce the input level, or (b) mute input levels, or (c) reduce the output level, or (d) adjust the trim pots, or (e) perform some combination of those adjustments. Furthermore, the 2 positions of the mute switches are difficult to discriminate, leading to setting errors.

FIGURE 7 Mackie CFX12 audio mixer
Source: http://www.crmav.com/recording/98/cfx12_mixer.shtml

In addition, there also have been problems in setting microphone levels so they could be recorded, in part because of the large number of microphones. Among them are (a) 2 microphones in the cab to pick up what subjects and a front seat passenger (often an experimenter) said, (b) the "voice of God" mic for the control room operator to talk to the subject, (c) "the golf mic," used to overlay commentary on the videotape not heard by the subject, (d) a backup ("floater") mic, and (e) several others. The current mic mixer (Shure M267) is being replaced by a Mackie DX810 8x10 crosspoint switcher (Figure 8), which has audio level meters for each channel, providing real time feedback of mic levels, a huge plus. Though it can be operated manually, most of the time a computer interface to the mixer will be used.

FIGURE 8 Mackie DX810 audio mixer
Source: http://mackie.com/products/dx810/index.html

Those with fewer audio inputs and outputs will be able to use simpler and less costly mixers, which generally lack the audio level/VU meters. Unfortunately, stand-alone meters (e.g., http://www.wohler.com/overviews/LM30-4.html and http://www.logitekaudio.com/mvmeter.htm) tend to be expensive, though there are some low cost kits available (http://www.quasarelectronics.com/meters.htm).

Recommendation 7. If feasible, to maximize screen luminance, position the image source near the driver and use retroreflective highway sign material for the screens.

The second-generation UMTRI Driving Simulator used engineering grade retroreflective highway sign material for the forward screen. In that simulator, the image generator was an overhead projector located behind the cab with a transmissive LCD flat panel as the image source (Figure 9). Because the top mirror of the LCD projector was just above the cab, the angle of reflection from the screen to the drivers' eyes was small, so the image appeared quite bright. In the third-generation simulator, the LCD projectors had to be mounted on the ceiling (because of the off angle projection mechanism, Figure 4), so using retroreflective material would not be beneficial. Furthermore, because of the geometry, a nonstandard wide-angle projection lens would have been required. Had a favorable configuration been achieved, the screen luminance would probably be 2-3 times greater than the images reflected from the current screens (drywall painted white).

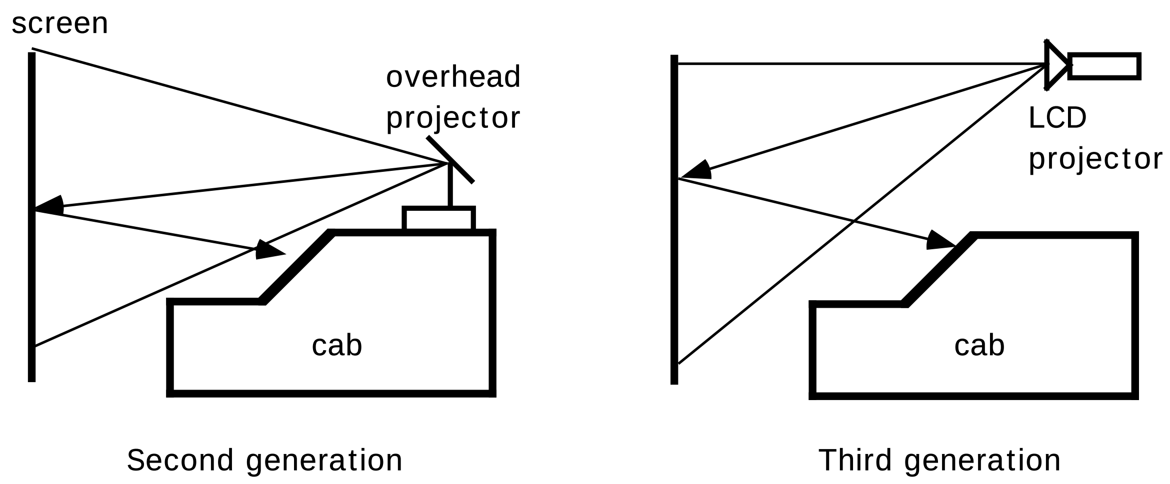

FIGURE 9 Comparison of Projector Locations

Those with more generous budgets for simulator development may wish to consider curved screens as an alternative to multiple flat screens. Keep in mind that not all projectors are designed to focus on a curved projection surface.

Recommendation 8. When in doubt, paint it black or cover it with black carpet.

Experience with retroreflective screens in the second-generation simulator emphasized the importance of light control to avoid unwanted reflections. The third-generation simulator bay has the look of a 60's dorm room, lacking only a UV light. Practically everything the subject would see except the screens is black. The ceiling is covered with black acoustical tile, the floor is covered with gray-black carpet tiles, and the walls are covered with black carpet and black drapes. Unlike flat black painted surfaces, there are no fingerprint problems when carpet is touched. Those with limited budgets may choose to use cheap black cloth without a sheen (i.e., not polyester or nylon) as a surface covering, with black velvet being a good choice.

Recommendation 9. To avoid unwanted images on screens, face all light sources other than projectors away from screens, and if that is not possible, put a barrier between them.

As a consequence, the main audiovisual rack was oriented away from the interior of the simulator bay, a door was placed behind it, and the control room was surrounded by a low wall, with an additional curtain as a partition.

Recommendation 10. Cover everything that is not a computer, a screen, or the car with sound absorbing material.

"Oh no, there is an echo, echo, echo in here." Even though the simulator is primarily a visual display system, there were at least as many issues with sound. To provide the desired 120-degree field of view and long sight distance, the third-generation system was installed in a new room, one that formerly was a computer room. That room had a raised false floor (since removed) on a concrete slab, a concrete ceiling, and 1 concrete wall. The other 3 walls were drywall.

Initially, the concrete floor and most of the walls were carpeted. When there was no equipment in the room, people talking to each other sounded like they were inside a box. Given the first experiment concerned acoustic warning signals, the room was unacceptable.

Working with an acoustics firm, sheets of rigid fiberglass covered with black cloth were selected to cover the ceiling. After several months of delay (oops, the cost is $200 more than the $5000 noncompetitive bid limit), the material arrived and was installed. This solution has been satisfactory. Had the authors been aware of the poor low frequency absorption of carpet early in the design, the walls would have been covered with fiberglass sheets and then covered with carpet (for durability). The topic of carpet flammability could merit additional consideration.

Acoustics seems to be a challenge for many simulators, especially those with wrap-around screens where either drywall or a painted metal dome is the screen surface. A fabric movie theatre screen is an interesting alternative. Fabric screens reflect light but pass sound. The desired sound attenuation could be obtained by mounting anechoic wedges or other material behind the screen. To get good low frequency absorption, one needs fairly tall wedges. Low frequency is important because much of the vehicle noise is below 250 Hz (Davis and Green, 1995), in contrast to conversation, which is in the 500 Hz-2000 Hz range. At the present time, Melamine pyramid foam, which provides the desired acoustic properties, is durable, and is available in dark gray, costs just over $6.00 per square foot for 4 inch (10 cm) thick pieces, and about half that price for 2 inch (5 cm) thick.

UMTRI is quite fortunate to have an unusual ceiling plenum design that tends to isolate heating, ventilation, and air conditioning (HVAC) noise, especially from blowers, and reduces the extent to which the air ducts serve as a transmission path between otherwise acoustically isolated rooms. Quiet HVAC is mandatory but very expensive and difficult to modify after installation.

Recommendation 11. Provide the operator a clear line of sight to the subject in the cab and all simulator image screens.

To observe subject behavior (to record task performance and look for signs of motion discomfort), operators in the control room need a direct line of sight to subjects. In the third generation UMTRI simulator, the control room was therefore on the driver's side of the vehicle, not the passenger side. Further, a direct line of sight to the simulator image screens allows the operator to verify the screens are updating properly and the desired images are appearing. Because the video rack blocks the line of sight to the rear channel, a mirror is used to verify rear channel operation.

Recommendation 12. Provide a discrete communications link between the simulator operator and the in-cab experimenter.

In some of the initial experiments on the third -generation simulator, an experimenter rode along with the subject to present task stimuli and monitor for motion sickness. There were times when the operator noticed something the experimenter should mention, but yelling across the room to say it was not appropriate. ("Don't forget to press the send button to complete a call.") Providing intercom style headsets with mics to the experimenter and operator should work quite well.

Recommendation 13. Provide wheelchair access to the cab.

Driving by individuals with disabilities is often studied in driving simulators. Required are wide doors to the simulator lab and sufficient space so that the door to the cab can be opened when a wheel chair is positioned nearby.

Recommendation 14. Provide at least 5 20 amp AC circuits.

In the second -generation simulator, there were occasional power problems, the most serious of which was a slide projector shutter momentary overloading a circuit, not sufficiently to trip a breaker, but enough to lock up a computer. Finding that problem took weeks.

To design the third-generation simulator, every major piece of equipment and its power consumption was identified, with multiple circuits being located side by side in the control room where demand was highest. Furthermore, service circuits were provided in the control room, in the cab, and around the room for cleaning equipment, power tools, auxiliary lighting, and other items. The UMTRI driving simulator has a significant amount of equipment, so power demands are greater than most. Circuits are very expensive to add after construction is completed.

Recommendation 15. Provide UPS for everything critical in case of a power failure.

In Michigan, there are thunderstorms in the summer and they can result in momentary power failures, though sometimes they can stretch to a minute or two. Computers do not recover well from unexpected shutdowns, especially the Linux OS computers that serve as the host and image generators. Sudden fan loss may cause the LCD projector bulbs to overheat and burn out, a $250 loss per projector. As a consequence, all essential equipment necessary to run the simulator is backed up by uninterruptible power supplies (UPS). Providing indefinite support was not cost feasible. Therefore, the goal was to provide power to ride out a momentary failure and those situations where if the failure continued for a few minutes, there would be enough reserve power to gracefully shut down the system, without losing the data collected up to that point.

GOAL 2: SUPPORT DEMONSTRATIONS.

Recommendation 16. Make sure that visitors see and hear everything subjects see and hear by allowing for any image to appear almost anywhere.

Research is not about just running subjects, but also convincing people to fund the research, and once the results are collected, presenting them. Many visitors to UMTRI want to see the driving simulator because the simulator exemplifies the Institute's research capabilities. Quite frankly, seeing the simulator in operation is much more interesting than going from office to office and watching people use Microsoft Word to edit reports. Visitor groups range from small (e.g., 3 people) to large (25) and adequate space for them to see everything must be provided. In the ideal situation, one would have a huge control room to accommodate visitors, and experimentation could continue uninterrupted. That space is not available at UMTRI, so generally visitors only see demonstrations, though at times there has been an extra observer in the control room during testing. However, even in the control room, the 5 to 9 inch (13 to 23 cm) video monitor images are too small to be seen by observers standing behind the experimenter (but are ok for a seated experimenter).

Therefore, the third-generation UMTRI simulator was designed so images from cameras as well as the driving scene can be presented on any 1 of the 3 forward screens or the rear screen. Typically, the driving scene appears on the forward center and rear channels and images from the face camera, foot camera, interior camera, or in-cab tasks are presented on the side screens so visitors can see what is occurring in the cab. This capability has also been used to aim and focus in-cab cameras. Eventually, images will also be able to be displayed on in-cab displays.

Furthermore, it is not only important to be able to see everything, but hear it as well. At UMTRI, visitors in the simulator room experience 4-channel sound present in the cab via duplicate set of speakers mounted in the corners of that room.

Recommendation 17. Get the NTSC output directly from the computers, not from external scan converters.

Implementation of the "any image, almost anywhere" concept is complicated because only some devices support switching between NTSC and computer video inputs. To provide for video recording of computer output, each computer video source (typically XGA) must be converted to NTSC (composite). Scan conversion options include (1) rack-mounted multichannel scan converters (which provide the best image quality but are expensive), (2) video cards with computer and TV outputs (a new development popularized by video games), (3) aiming a camera at the each XGA display (which provides a stable image for LCDs or CRTs that are synchronized with the camera), and (4) using low cost external scan converters. Initially, low cost external scan converters were used with each XGA signal being split (using a Belkin Expandview or similar device) with outputs going to the display of interest and a scan converter (Focus Enhancements TView Micro) powered by a USB hub. This approach was successfully used in the second-generation simulator, where there were few video sources. In the third-generation simulator, the increased number of channels decreased reliability and made tracking down problems (with 3 devices/channel and the spaghetti between them) difficult. Changes in TView power requirements (and the number and types of hubs needed) further complicated matters. These device triples are being replaced by dual output video cards for the in-cab images (speedometer/tachometer cluster, touch screen, HUD). Eventually, dual output video cards will also be installed in the simulator image generators.

Recommendation 18. Accommodate TV crews.

Because of their visual nature, simulators are not only of interest to potential sponsors and community organizations, but also to reporters looking for stories, especially TV. TV crews appreciate direct access to both the audio and video signals so they can record background shots (B-roll). They also need power for their lighting equipment. Lighting is critical in dark, all-black rooms typical of simulators.

GOAL 3: FACILITATE CONFIGURATION VERIFICATION AND TROUBLESHOOTING.

By far, most of the simulator hours are spent developing simulations, not testing subjects or giving demonstrations.

Recommendation 19. Diagram everything.

Although there was a general concept as to how the simulator was to be wired and there were incomplete wiring diagrams for the video system, they were not developed for the audio system. Hence, finding audio system problems was a challenge. Furthermore, there were major gaps between updates of the video-system wiring diagram, so there were many patches and ad hoc fixes to problems.

The wiring diagrams should be handled as engineering documents. Because of the dynamic nature of the simulator during the early stages of its life, wiring diagrams are living documents. Modifications to the simulator should be preceded by engineering drawings showing the changes planned.

Recommendation 20. Label everything.

In the initial studies in the third-generation simulator, not everything was labeled, and because of the dynamic nature of the design, some things were mislabeled. ("I want to show the over the shoulder camera in quad 1 of the VCR. Does anyone know the input and output channel numbers?") Particularly troublesome were the input and output bulkhead panels on the main rack, where connections were too close together. Consequently, a great deal of time was spent tracing wiring to determine the cause of problems. Labeling cannot be stressed enough.

In addition, there were also problems associated with unlabeled null modem cables being used as serial extension cables, and serial cables for which only a subset of the pins were connected.

Every wire bundle and every cable should be labeled at both ends, even if the device to which it is connected is labeled. Names should indicate the source (cab video 1, over the shoulder camera) or destination (monitor 1, input 1) to which it is connected or both. Devices (monitors, bulkhead panels, etc.) should also be labeled so when items are disconnected, they can be reconnected quickly. Furthermore, as a precaution, rings of colored tape can be used to provide redundant color-coding (e.g., monitor 1 cables are green, monitor 2 are red). To support "label-mania," 2 Brother PT-1800/1810 label makers were purchased and a carton of 1/2 inch (13 mm) tape. If the label printer can be connected to a data base of cables (not possible for the Brother label maker), the effort to print labels is substantially reduced and the labels are more likely to be consistent with the documentation. Finally, a periodic inspection is needed to make sure that when equipment is reconfigured, the labeling reflects the new configuration.

Recommendation 21. Develop alignment mechanisms and calibration files for projectors.

Multiple channel systems, especially if there are multiple forward channels, have alignment problems not present in single channel systems. Early on, it is important to verify the horizon for each channel is at the proper height, and for adjacent video channels, that they are aligned properly so when an object moves from 1 channel to another, the object does not jump across screens or is temporarily not visible. If a system is well designed, once channels are aligned, they should remain aligned for a long period of time.

For the UMTRI implementation of the DriveSafety simulator, the 3 forward channels were impossible to align using the vendor supplied projector mounts as the friction mechanism did not allow smooth movement and fine adjustments, and because over time there was noticeable slip in the position setting. Those mounts were replaced with Manfrotto 410 geared tripod heads (Figure 10) to provide for easy subpixel adjustment of image pitch, roll, and yaw, saving days of work. To support calibration, custom polar coordinate and other grids (with numbered markings) were devised so exact values for fields of view and image shifts could be determined.

FIGURE 10 Manfrotto 410 geared head
Source: http://www.manfrotto.com

Recommendation 22. Develop test software for the audio system.

The first experiment on the third-generation simulator concerned the use of directional sound to provide auditory warnings. ("The sound is coming out of the wrong speaker again. Are you sure the volume for the left and right are the same?") To overcome these problems, software was developed to speak the name of the speaker ("left front") or speakers ("right side") being activated, having both single utterance and repeated utterance modes. This software runs on the same computers that generate the sounds in experiments. Due to time pressure, this software did not exist when the simulator was first used, making debugging very difficult.

Recommendation 23. To provide 4-channel sound, use a 4-channel card, not 2 computers each with stereo.

The initial simulator design used 2 computers (each handling 2 channels) to generate 4 channel output. This solution, taking advantage of existing equipment, was thought to be low cost. In fact, had 4-channel sound cards been used, the total cost would have been less because the 2+2 system has a much higher development cost and the software development time is longer.

Recommendation 24. Provide both front and rear access to all equipment racks.

There is a constant need to check equipment connections invariably located in the back of the equipment. There was rear access to the main audiovisual rack (via a door in the control room wall) and all of the computer racks were on wheels, so they could be rolled away from the wall for access. When the computer racks were moved for inspection or back into place, cables were pulled out of their connections when there was not enough slack or stress relief for cables. Had the space been available, an access "alley" to the back of the computer racks would have eliminated the movement related disconnects. Mounting the equipment racks on large diameter casters was a good decision.

Recommendation 25. Put all of the computers and video equipment side by side in the control room.

Initially, some of the computers were behind the cab on the floor so they would be near the devices they controlled (e.g., USB is limited to 5 meters). As a consequence, when there was a problem related to those computers, monitors and keyboards were connected to them and people worked sitting on the floor. It was a mess. Since then, devices have been found to allow driving USB over CAT5e (http://www.networktechinc.com/usbc5.html) so longer cables can be used and the computers have been moved to the control room. The time to find problems has been reduced and the installation is much neater.

Because of space limitations, the computer and AV racks are on opposite walls, with the connecting wiring running through several metal channels. Had the racks been side by side, tracing wiring to solve problems would have been much easier.

Recommendation 26. The rack space needed is at least 50% greater than the best estimate.

The original plan called for installing all of the audio-visual hardware in a single 84 inch (2.1 m) high 19-inch (48 cm) wide rack, which was too small because there was no room for expansion as equipment was added after the initial design. There is a natural desire to use all of the rack space available and not follow the standard practice of have 1 rack unit between devices for cooling. Therefore, some audio-visual equipment was moved elsewhere, adding to the cabling needed and opportunities for failure.

Recommendation 27. Use oversize raceway for running data lines, not conduit.

Metal conduit, the initial choice to protect the wiring, is inexpensive to purchase, but expensive when the cost of labor to add wiring is included. Metal raceway is therefore recommended. There is one 1-1/2 x 6 inch (4 x 15 cm) channel from the control room to the vehicle cab. Two would be ideal. As a consequence, some cable was outside the channel and unprotected.

GOAL 4: PROVIDE HIGH QUALITY AUDIO AND VIDEO SIGNALS.

Recommendation 28. Independently check the quality of all hand made cables.

The rack location and large number of cameras led to the on site fabrication of over 1000 feet (305 m) of custom RG-6 cables. Unfortunately, the hinge pin on the crimping tool broke early on and no one noticed this, resulting in a large number of faulty cable end crimps that had to be redone. Independent, professional inspection using an ohmmeter (or an electronic cable testing device) would have caught the sloppy work and led to fewer video problems to be resolved.

Recommendation 29. Isolate the speaker lines and data lines from all power sources, and double check all grounds.

"The speakers are humming again." Hum generally began when the speaker lines or cab components were moved for maintenance, especially the subwoofer (which has a large magnet to drive the speaker). Problems also occurred when the audio system power supply was shared with nonaudio devices.

In addition, where feasible, data lines should be isolated from microphone cables. Data line signals are typically several volts whereas microphone signals are at microvolt levels. Isolation can be accomplished by using a separate conduit or raceway, or a separate channel in a multiple channel raceway, as even perfectly balanced microphone cables are susceptible to interference. Cable shields only provide electrostatic, not electromagnetic shielding.

Recommendation 30. Use quality audio and video parts to assure quality signals

Table 2 elaborates on this recommendation.

TABLE 2 Recommendations for Parts

Part	Comment
Use quad shield video cable	Because there was so much cable, there were many opportunities for signal loss and interference problems. To provide desired signal quality, heavy duty RG-6 video cable (Belden 1189A) was used, not RG-59. Unfortunately, heavy-duty cable requires large bend radii and attaching connectors can be difficult. If plenum rated cable is required for fire safety, 1189 will not be acceptable.
Use coax monitor cables with embedded ferrite	Long RGB monitor cable runs are susceptible to interference and ordinary shielded cable is inadequate. Appropriate cables can be purchased from GB Electronics.com, Startech.com, CablesToGo.com, L-com.com, and often at the best price from Insight Computers (insight.com).
Use compression not crimp connectors	Most cable and broadcast TV installations use F type compression connectors. Compression connectors are becoming more popular for other purposes as they are easier to install than crimp connectors and do not have the sharp edges that cut hands and cables. Digicon compression type BNC connectors (the desired connector) are available from Cencom94.com among other sources.
Use active video splitters	There are too many signal quality problems with passive splitters. Consider the Startech model ST122PRO 2 port splitter (that supports XGA) from insight.com or buy.com, or if VGA is used, a Belkin ExpandView (model F1D068) has proven acceptable. For NTSC, use multiple output distribution amplifiers (e.g., Kramer VM-1044) instead of passive splitters.
Use 75 ohm, not 50 ohm video connectors	To connect cables, Ts were purchased at the local Radio Shack store. Careful inspection revealed they were 50-ohm impedance, not the 75 ohm desired (http://sosnick.uchicago.edu/BNC_50_75.html).
Provide phantom power for all microphones	"There is not sound on the tape. The mics are not working again." Because the mics in the cab are far from the control room, phantom power to drive the mics is desired. This is often the case for lavalier mics (such as the Audio-Technica 831b, selected for its quality output and small, inconspicuous size).
Fit all mics with XLR connectors.	The cable between the cab and control room is susceptible to interference. Interference is less likely when balanced lines are used.
To get realistic road feel, use a digital amp to power the bass shakers.	Digital amps are superior to the analog amps. The Aurasound (aurasound.com) model AST-3B-4 is recommended.

WHAT ADVICE DO THE AUTHORS HAVE FOR OTHERS WILLING TO SUFFER THROUGH DEVELOPMENT?

One might get the impression for this paper that the third-generation UMTRI Driving Simulator is a total disaster. It is not. The team had many years of prior experience with another simulator, so the team was well aware of the problems that could occur. This experience helped reduce the number and severity of problems experienced, though the team is still learning. The simulator has been used to produce quality research, though stress on the team (and research sponsors) was greater than desired.

Beyond the specific recommendations listed previously, the authors would like to offer four general recommendations.

First, push hard for a very big room (say at least 40 x 40 feet (12.2 x 12.2 m)). Not only was there a compromise on sight distance from the cab to the projection screens, but the arrangement of equipment was suboptimal, with lots of additional wiring, cable trays, and labor to assemble and debug the simulator. Many are envious of the space at UMTRI because the screens at other sites are just in front of the cab, and equipment is crammed into a tiny room. Simulators are showpieces and those making space decisions need to keep that in mind.

Second, after the cab is in place, allow for 4-6 months without studies to complete installation and collect calibration data. Because simulators are so expensive, there is great pressure to use them immediately to generate revenue. Consequently, too many things are patched ad hoc to get them working to make study schedules, and patches must be redone later. Further, staff time was wasted trying to determine why mics, speakers and other equipment were not working.

Third, plan for redesign after the first few studies. Iterative design (reference 11) not only makes sense for user interfaces, but facilities to test them as well. Simulator users rarely have enough experience to know everything they will need to know in advance. Cameras will need to be added and equipment rearranged to meet research needs.

Fourth, it was said before but bears repeating, label and diagram everything! The lack of documentation is the scourge of student efforts.

FINAL ADVICE

One final caution for those contemplating purchasing a driving simulator. The major cost hurdle is NOT the initial funds for the acquisition, but the ongoing costs of the expert staff to maintain the system (their salaries, benefits, and associated overhead), the cost of an annual maintenance contract (typically 25% of the initial software cost), and the costs associated with keeping the hardware and software current. In the case of DriveSafety products, there is a great deal of sharing of code and information across sites. One cannot benefit from that sharing if a simulator is not current. As an example of some of the costs, UMTRI expects to replace all 4 video projectors (at $4000 each) and the image generators (another $2000 each) every 3 years and the video cards ($200 each) every 2 years.

In spite of these hurdles, if there is a group of scientists who contemplate intensive use of a driving simulator over a decade, if there is skilled technical staff who work directly for them, if there are funds for acquisition and maintenance, and if the space exists, then others are encouraged to get in the simulator game. Driving simulators can be wonderful tools for doing research that will help reduce motor vehicle fatalities. The authors hope that the recommendations in this paper are useful to others and would appreciate hearing from them.

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NOTE

The authors have no financial interest in any of the companies mentioned. Products and web sites are mentioned for the convenience of others developing simulator facilities.