

How Driving Simulator Data Quality Can Be Improved

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Abstract

This paper examines problems commonly found in fixed-based driving simulators that lead to imperfect replication of real driver behavior and performance, and solutions for those problems. Those problems include (1 and 2) the standard deviation of lane position is either too small or too large, (3) subjects drive all over the world, and (4) too fast, (5) subjects slow down too much or follow a lead vehicle from too far when distracted, (6) speeds are too steady, and (7) drivers take too long to respond to signs. Some of these problems occur because sometimes vehicles are too stable (time-to-line crossing values are too large) or, because there are no handling imperfections (e.g., mismatched tire pressures), road imperfections (e.g., potholes), or environmental disturbances (lateral or head/tailwinds). Also worth considering is adjusting the feedback to the driver (e.g., boost the steering wheel torque to compensate for the lack of motion cues and shaking the steering wheel when driving on a rough surface such as a shoulder or off-the road) to encourage subjects to drive on the road.

Introduction

This paper is intended for those that manage simulators now, use them for studies, or are contemplating acquiring a driving simulator. The paper shares its practical emphasis with a prior paper by the author on design recommendations for driving simulator audio-visual systems (Green, 2003).

The use of driving simulators for research and other purposes continues to increase. The purchase price of driving simulators has decreased considerably, and recognition of motor vehicle crashes as a major public health hazard has increased, especially the safety implications of using devices such as cell phones while driving.

The literature on driving simulators concentrates on how they are used to conduct experiments, though there are papers concerning simulator design and evaluation. (See Brouwer and Ridder, 2003.) This paper has a somewhat different emphasis, providing suggestions based on personal experience and the literature as to how driving simulator research, in particular in fixed base simulators, can be improved. The central thesis of this paper is that significant enhancements in quality would occur if the values measured in simulators more closely resembled those of on-the-road driving. (See also Greenberg, undated.) Admittedly, the recommendations of this paper would be more convincing if each recommendation was supported by carefully controlled experiments and statistical analysis. However, the recommendations are well supported by common observations, are robust, and make sense. Accordingly, scarce experimental resources are best allocated to more uncertain matters.

When developing driving simulations, there are at least 3 specific goals to keep in mind.

Goal 1: Replicate real driver behavior and performance.

Goal 2: Make driving simulator studies easy to conduct, that is plan, execute, reduce, and analyze.

Goal 3. Do not harm subjects.

This paper concerns the first goal.

Why is replicating real driver behavior and performance a concern? In a perfect world, all aspects of a simulator and driver performance would mirror the real world. Text resolution for signs would be identical, torque levels on steering wheel would be the same, and as a consequence, the fixation durations on signs and the number of lane exceedences would be the same. However, in simulators, especially fixed-base simulators, compromises are necessary. Those compromises compensate for the lack of motion cues, and limitations in the visual and auditory systems. However, even in the best simulators (e.g., Daimler simulator in Berlin (Drosdol and Panik, 1985), the Ford Driving Simulator (Cathey, Artz, Grant, and Greenberg, 2000; Greenbert, Artz, and

Cathey, 2003), VTI (Nilsson, 1993), TNO (www.tm.tno.nl/downloads/2003vh5e.pdf)), there are sometimes differences in driver performance between on the road and in driving simulators. For moving-based simulators, the developers have often gone to great lengths to identify road-simulator differences and minimize them (e.g., Grant, Artz, Blommer, Cathey, and Greenberg, 2002).

There does not seem to be a similar level of effort for fixed-base simulators. Green, Cullinane, Zylstra, and Smith (2004) reviewed measures collected in driving studies including the standard deviation of lane position, the most common measure. Figure 1 shows the data split by where the data was collected. Each data point in the figure represents whatever means could be retrieved from a particular study (e.g., older subjects driving in a baseline condition), taken from 36 well known studies. Given there were many differences in the underlying data (due to subject age, the type of road driven, speed, the level of distraction, etc.) some variation in the mean standard deviation of lane position is expected. However, what is striking is the much greater range in the values reported for simulator studies (both fixed and moving base combined), spanning a range of a factor of 20. Some of that increased variability may be because high-risk studies (that lead to the greatest variability) are only conducted in simulators or because subjects cannot die in simulators, so they sacrifice steering performance rather than in-vehicle task performance in challenging dual task conditions.

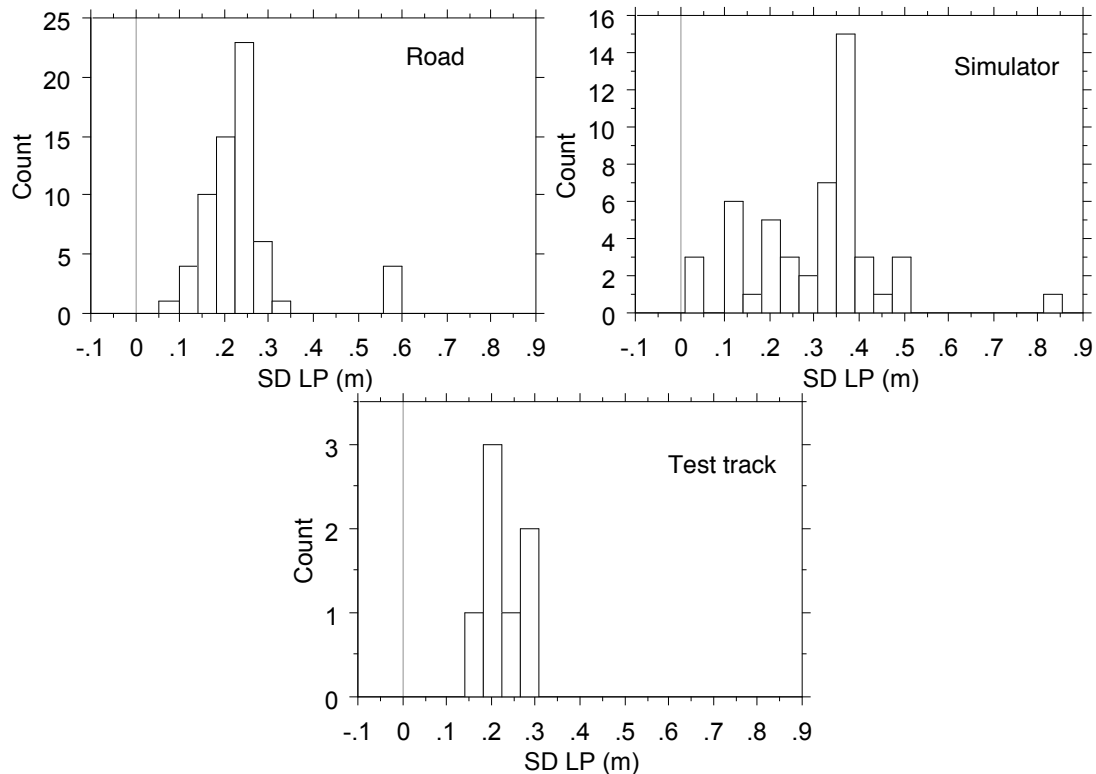


Figure 1. Standard Deviation of Lane Position for Various Contexts

However, discussions with other scientists, a review of their backgrounds, and insights from published reports suggest that experimenters are often most interested in obtaining statistically significant differences between conditions, and as a consequence the mean values and their reasonableness are downplayed. In fact, there are often situations where experimental manipulations are carried out to accentuate differences of test conditions so differences can be obtained within the time limits of a simulator study. However, when the focus shifts to the mean values obtained (by engineers, not the psychologists who may have conducted the research), the lack of credibility of the results can lead to a lack of acceptance of the research. (“No one really has a standard deviation of lane position that large.”) Experimenters need to verify that the performance data (in particular, means and standard deviations of them) obtained in simulators resemble what would be obtained on real roads.

Why are the simulator and on-road data sometimes different?

To a large extent, lateral position variability when driving in a lane depends on the inherent stability of the vehicle (Norman, 1984; Post and Law, 1996; Higuchi and Sakai, 2001; Artz, Cathey, Curry, Grant, and Greenberg, 1999). A measure of stability is time-to-line crossing (TLC), the time required for a vehicle to begin to leave the lane if the driver stops steering (van Winsum, Brookhuis, and deWaard, 2000). TLC may be determined by either letting go of the wheel, or more commonly, maintaining a steering angle until a tire touches a lane boundary. This measure of on-center handling is usually obtained by driving on an expressway in light traffic, driving down the center of the lane with the vehicle pointed straight ahead, and performing the hold or let go maneuver, regaining control when a tire touches an edge mark. For the hold maneuver, bracing the driver’s hands to inhibit wheel movement provides more consistent results. The advantage of the “let go” method is that it eliminates the opportunity for the driver to inadvertently provide corrective input.

Experience suggests that TLC values on the order of 5 - 10 seconds (determined by either method) are reasonable, but the value depends on crosswinds, road roughness, the speed driven, the design of the suspension system, tire pressures, the extent of “grooving” in the lane, and so forth. Unfortunately, there is not much data in the literature concerning the relationship between TLC and any of these parameters. There is a belief, however, that TLC for contemporary vehicles is less than for vehicles from a decade ago. Again, as was noted previously, the standard deviation of lateral position is affected by vehicle stability, one measure of which is TLC.

Problems and Recommended Solutions

Problem 1: The standard deviation of lane position (SDLP) is sometimes too small.

Many driving simulators lack the imperfections that existing in real vehicles driven on real roads under real environmental conditions. In real vehicles, especially in older vehicles, sometimes the pressure in the front tires is not equal, causing the vehicle to “pull” to one side. Drivers readily notice differences of a few pounds of pressure.

Real roads have surface imperfections--unevenness, potholes, cracks, and so forth. Those imperfections perturb the vehicle's path. For states with long freeze-thaw cycles (e.g., Michigan), roads may be significantly degraded, especially early in the spring. The author has yet to see a driving simulator study where road roughness measures such as the Present Serviceability Rating (PSR) or the International Road Roughness Indicator (IRI) have been reported (Sayers and Karamihas, 1996; Karamihas, Gillespie, Perera, and Kohn, 1999, U.S. Department of Transportation, 2003).

The vehicle path is affected by wind in the environment, wind that is variable in its speed and heading, and whose relative direction changes as the vehicle follows a curving road. There is almost no discussion in the literature of the statistical distribution of wind gusts imposed in driving simulators.

If a simulated vehicle has no imperfections in its dynamics, and if roads are perfectly flat and even, and if there is no wind, then it is possible to align a vehicle on a straight road, and if the steering wheel is locked in position (by holding it tight), to drive for 20 seconds or so before leaving the lane. This does not occur in real driving. In fact, clever experimenters have found that the safest way to do a telematics task may be to line the vehicle up almost perfectly, then let go of the steering wheel for 20 seconds to attend to the telematics task, and at the last possible moment, return to steering.

Recommendation: Make sure that the driving simulator has some low level of cross path disturbance, usually simulating a cross wind, that will cause the simulated vehicle to deviate from its path. As a simple first step, the desired crosswind intensity can be computed as the sum of 3 nonharmonic sinusoids, selecting amplitudes so there is a mixture of drifts to the left and to the right. The tracking literature shows that people cannot memorize patterns of 3 harmonics, so there should be little difference in driving performance with a 3 harmonic cross wind and a completely random one, assuming the amplitudes are equalized. Three harmonics should be easier to implement.

Problem 2: The SDLP is sometimes too large.

Practice does make perfect, and in the case of driving simulators, drivers need to be accustomed to the handling. McGehee, Lee, Rizzo, and Bateman (2001) provide data suggesting about 3 minutes are needed to become familiar with a simulator, a level of practice that almost all simulator experiments provide. Hence, it is unlikely that lack of experience explains why SDLP is sometimes too large.

As an aside, the author has found that when subjects initially experience difficulty with driving a simulator, it is because they overcorrect, leading to excessive scene motion and potential motion discomfort. A solution is for the experimenter to also hold the wheel while the subject steers, demonstrating that fewer steering inputs are needed. Generally, about 10-15 seconds is enough for subjects to get the idea.

How then, does one compensate for the missing motion cues that seem to be the root of the problem?

Recommendation: To compensate for the missing motion cues, increase the steering torque to levels above that for the vehicle being modeled, with the level determined by having the experimenters drive, recording the steering performance and adjusting the torque until simulator values match those recorded on the road. At increased torque levels, the vehicle will “feel” right to everyone except vehicle dynamics experts.

Problem 3: Subjects drive all over the world.

Because simulators can have game-like quality, a significant number of visitors involved in demonstrations are curious as to what off-road is driving is like, and will head off into the trees. Many simulators, because they designed for on-road driving, do not handle the off-road case very well. In particular, the vehicle and steering wheel shake are missing. Since there are no negative consequences for off-road driving, off-road driving becomes more acceptable.

Recommendation: When a vehicle tire falls from the pavement edge on to the shoulder (usually the right front tire off the right side of the road), the simulator should “jerk” the steering wheel, that is, provide a torque pulse to the steering wheel for that action, and this action should occur as each tire leaves the road. Furthermore, when the vehicle is off the road, shake the steering wheel aggressively (as if driving on a rough surface) to discourage departing from the road. Also, make the wheel shake more aggressively as each tire transitions from the shoulder to grass or dirt. Finally, as the vehicle returns to the road, additional torque pulses are needed. The torque pulse and shake features were incorporated into the second-generation UMTRI driving simulator. The resulting lack of control discouraged off-road driving and lead to fewer extreme lane positions.

Recommendation: Provide sounds commensurate for driving on the shoulder (e.g., over gravel) or completely off the road when appropriate. In the second-generation UMTRI driving simulator, these sounds provided additional situation awareness, and helped reinforce the notion of staying on the road.

Recommendation: Demonstrate to subjects that control problems that occur when driving off road. In familiarization runs of prior UMTRI studies, subjects were instructed to carefully drive so part of the car was on the shoulder. Older subjects were sometimes reluctant to do so, but complied. Younger subjects were more willing, probably because of their experience with video driving games, where there are no severe consequences of driving in an unsafe manner. Subjects from both age groups were a bit startled when the lack of control occurred, even though they were forewarned. This approach combined with torque and auditory feedback was effective in encouraging subjects to stay on the road, and brought SDLP to more reasonable levels for real driving.

Recommendation: Where they are likely to be present, Botts’ dots (raised pavement markers, <http://www.snopes.com/business/origins/bottsdots.asp>) should be provided. Driving over them leads to a popping sound from the tire, and generally a very slight twitch to the steering wheel, sounds and forces that may be exaggerated in simulation to encourage lane-keeping behavior. This was found to be the case in the second-generation UMTRI simulator, though this cue was less effective than those associated with driving on the shoulder.

Recommendation: In some places where the shoulder is paved, grooves are cut into the shoulder, so that if a sleepy or inattentive driver leaves the right lane, the sound (and slight steering wheel shake) may wake them up and get their attention. These cues should also reduce off-road driving in a simulator, though the author does not know of any simulator in which these cues have been implemented.

Problem 4: Subjects drive too fast.

In many driving simulators, the field of view is narrow (often 1 40-degree channel), so the peripheral speed cues (in addition to motion cues) are missing. Even when simulators have more than 1 forward channel, experimenters turn those channels off to reduce the occurrence of motion sickness.

Recommendation: Subject speed can be controlled by traffic. For example, for multilane highway driving one can have a platoon of vehicles ahead of the subject that adjust their position relative to each other (and even change lanes), but form a barrier that subjects cannot pass. However, they can speed up and slow down in a natural manner so the subject cannot fix their speed (e.g., Tsimhoni, Smith, and Green, 2004).

Recommendation: Engine sounds are related to RPM, and though subtle, do suggest driving speed. If someone is asked what a car sounds like, most people will utter something like “vroom” even though most cars are extremely quiet. Thus, as long as auditory warnings are not being assessed, where auditory masking is an issue, vehicle sound levels can be increased above their real values to enhance the sense of speed.

Recommendation: If additional cues are needed, one could have subjects drive on a concrete road with filled expansion joints, making the “pop” sound each time one is crossed. Probably, the effects of these 2 forms of auditory feedback on driving speed are subtle.

Recommendation: It may also be possible to shake the steering wheel very slightly when the speed is excessive, simulating driving a car with poorly balanced front tires.

Recommendation: Increasing the amplitude of a seat shaker as vehicle speed increases provides subtle cue for speed. This cue is provided in many fixed base simulators.

Problem 5: Subjects slow down too much or follow lead vehicles from too far away when distracted.

On a public road, speed decreases on the order of 5 mi/hr are not unusual when subjects are distracted. In a driving simulator, decreases on the order of 10 mi/hr or more can occur. On public roads, people who drive too slowly are likely to be rear-ended by following traffic.

Recommendation: To provide that real world pressure to maintain speed, have the subject followed by 3 vehicles (visible in the rear view mirror). The first, a small car, should provide 2 quick, high pitched toots when the subject falls significantly below the speed limit. Five mi/hr seems to be reasonable. If the subject slows down further, say 5 mi/hr

or does not respond by returning to the posted speed (say after 10 seconds), sound the horn from a large car, the second vehicle that is following. That blast should be a bit longer than that from the small car, suggesting annoyance. If the subject fails to respond to the second car, say in another 5-10 seconds, then sound the air horn of a following truck. The air horn should be louder than the other horns. Because of its resemblance to the real world, subjects know what to do when other drivers honk, though mentioning this could occur is helpful to subjects. Furthermore, even when repeated many times in an experiment, subjects invariably speed up as desired. This cueing strategy proved to be very effective in an UMTRI study of the use of lane departure and curve speed warnings while distracted (Sayer, Cullinane, Zylstra, Green, and Devonshire, in preparation). There is no reason why this speed cue could also not be applied to control following distance.

Problem 6: Speeds are too steady.

Speed variability is lacking because many of the slight changes in grade or headwind/tailwind perturbations are missing. Adding in slight grades in many simulators is not easy. Adding in slight winds is relatively easy.

In some simulators, the trick to driving at a steady speed is to slide one's foot to the right of the accelerator and brace the foot against the transmission tunnel. In this manner, driver induced errors in speed are minimized.

Recommendation: Add a varying headwind/tailwind to the simulation based on 3 nonharmonic sinusoids as described earlier. It is probably best if the crosswind and headwind/tailwind are not correlated, which can be achieved by using different frequencies for the 2 wind components.

Problem 7: Drivers take too long to respond to signs.

Because the resolution of a sign as presented in a simulator is much lower than in the real world, drivers must be much closer to signs in order to read them, increasing the time to read them from when they first appear. Most driving simulator image systems fall far short of the resolution of the human visual system (roughly 1 minute of arc, or .0167 degrees). A typical driving simulator will use an XGA projector (1024 x 768) covering 40 degrees, so each pixel covers .0391 degrees. To match the human visual system, at a minimum of 2400 pixels horizontally is needed, which is more than double the current horizontal resolution, which will require more than quadrupling the display bandwidth, though a quadruple XGA (QXGA) projector (2048 x 1536, 3.2 megapixels) comes close to what is needed (http://www.jvcpro.co.uk/item/index_html?item=DLA-QX1). Currently, as an example, JVC makes a QXGA projector (DLA-QX1G) that has an advertised contrast ratio of 1200:1 and a maximum output of 7000 lumens, clearly quite good for most simulators. However, its suggested list price is \$225,000 (without a lens), an amount sufficient to purchase and install a current fixed-base driving simulator. A reasonable cost projector (say \$2000-\$4000) of sufficient luminance for this purpose is probably 5-10 years into the future.

Currently, reasonably priced UXGA (1600 x 1200) 2000 lumen projectors, a next logical step up from XGA, are beginning to appear in the \$2000 - \$4000 range, though one could

pay several times that amount for a UXGA projector. In a simulator with multiple forward channels, UXGA projectors could be set up so that if each projector covers a smaller field of view (26.67 degrees to be exact), the desired resolution could be achieved. However, more projectors would be needed and there would be more seams (between projector images) in the driver's visual field and the vertical field of view would be reduced. Furthermore, each projector needs an image generator (computer) to control it, increasing the system cost and complexity.

Recommendation: The interim technical solution is simply to make signs much larger so they can be read. Doubling their height and width to obtain close to the desired resolution is a solution, but then signs look odd. Some choose to increase their size by 50% as a compromise of legibility and appeal, and some make no changes.

Recommendation: In addition, simulator vendors should continue to review using UXGA-capable display cards and UXGA projectors to make signs easier to read.

Closing Thoughts

There are a number of steps that can be taken to improve the quality of data collected using driving simulators, in particular, those that lack motion. These improvements, mostly accomplished by simulator manufacturers, will lead to results in driving simulator experiments that will more closely resemble the real world and are therefore more likely to be accepted by practitioners.

However, all of the responsibility is not in the hands of simulator manufacturers. Those that use simulators need to be vigilant with regard to the data they collect, and need to verify that the values reported are indeed reasonable for real driving, and not just that differences between test conditions of interest are statistically significant. This will require some effort to "tune" driving simulators before they come on line. This is generally very difficult to do because once installation of a simulator is complete, there is considerable financial pressure to immediately generate revenue to cover costs, that is, run studies. Experimenters are encouraged to take the time to "get it right."

Driving simulators have an important role to play in human factors and safety research, and that role will continue in the future. Success in that role depends on the credibility of the research results, and as described here, results that can be enhanced by some simple improvements in driving simulators.

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