Overcoming Sign Design Challenges in the Central Artery Tunnel Project

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ABSTRACT

Boston's Central Artery (Interstate 93) through downtown Boston is being reconstructed as a 1.5 mile long tunnel. Within the tunnel itself are several exits that require guide signing for motorist safety and efficient traffic operation. Design and placement of this signing faces challenges due to low ceiling height (17.5 feet) and horizontal and vertical curvature within the tunnel that reduce the distance from which signs can be seen by motorists. Within the confines of the tunnel, guide signs may be more easily blocked from view by large trucks, due to the lower than usual mounting height above the roadway.

One of the improvements – from a traffic operations standpoint – of reconstructing the Central Artery is to reduce the number of exits and entrances from Interstate 93. Currently, there are a total of 27 exits and entrances (two-directional total) in a distance of about three miles. This number will be reduced to a total of 14 exits and entrances. Yet, in the tunnel portion of the project there will be a total of 7 exits. Three exits will be compressed into a 4,100 foot long southbound tunnel segment.

The above conditions may mean that drivers – especially unfamiliar drivers – will have difficulty obtaining the guidance information they need to find the proper exit. This will lead to driver frustration and may also lead to a reduction in safety due to abrupt lane changing and other maneuvers. To overcome these problems and to improve the sign design and placement, a study using a driver simulator was undertaken. A computer generated roadway through the tunnel was developed to replicate the tunnel geometry (including horizontal and vertical curvature and ceiling height) and the placement of signs. Signing alternatives were developed and test subjects drove through the simulated tunnel to evaluate those signing alternatives.

This paper will share the authors' experience in using a full-scale driving simulator as a tool for improving freeway guide signing.

INTRODUCTION

The Central Artery / Tunnel project in Boston is regarded as the largest public works project currently underway in the United States. The entire project includes a new four lane highway tunnel under Boston Harbor (the Ted Williams Tunnel, opened in 1995), an extension of I-90 through South Boston, a new cable-stayed bridge across the Charles River for I-93, and the reconstruction of the existing Central Artery (I-93) through downtown Boston. This entire set of projects is currently estimated to cost $14 billion. Completion of the new facilities is scheduled for 2003 and the old elevated Central Artery facility will be demolished during 2004.

This paper deals with the reconstruction of the existing Central Artery (I-93) through downtown Boston. Originally built in the 1950's, this facility is mostly on elevated structure, with a shorter segment in tunnel. The new facility is being built as an underground tunnel, in most locations directly under the existing elevated structure.

The new tunnel will be 1.5 miles long and will generally be four lanes in each direction with the two directions of travel physically separated by a dividing wall. A fifth auxiliary lane will exist in many locations in advance of exit ramps and downstream from entrance ramps.

CHALLENGES TO PROVIDING GOOD GUIDE SIGNING

The physical characteristics of the tunnel include horizontal and vertical curvature and a ceiling height of only 17 feet in many locations. These characteristics present challenges to providing good guide signing for motorists. The low ceiling height, combined with a 13.5 foot maximum legal height for trucks and allowing an overhead buffer space of six inches means that all overhead guide signing can be no more than three feet in height. This height is substantially shorter than typical overhead guide signs, which are often six or more feet in height. The shorter height makes it more difficult to include the amount of information that may be needed to provide adequate motorist guidance, especially when standard letter sizes are used.

On most freeway facilities guide signs are at least 18 feet above the pavement. One of the consequences of signs being only 14 feet above the pavement in the Central Artery Tunnel is that motorists' view of the signs can be more easily obstructed. For example, if a motorist is following behind a large truck, the sign will be obscured by the truck for a longer period of time and will be fully visible for a shorter period of time.

On straight tangent sections of roadway with constant grade there are long lines of sight and overhead guide signs are often visible from long distances. In this kind of situation a sign can usually be seen long before the legend on the sign becomes legible. When the motorist is sufficiently close to read the legend, there is usually a very adequate amount of time to read the sign message before the sign disappears from view behind the roof of the vehicle.

In contrast, the line of sight in the Central Artery / Tunnel is often restricted due to horizontal and vertical curvature of the tunnel. As a result, many signs do not come into view until the distance to the sign is less than the legibility distance. The result is a shorter period of time to read the legend than exists on straight sections of roadway. The reduced reading time can be very problematic when the sign message requires an action, such as exiting from the roadway.

An additional challenge for tunnel signing is that the new tunnel will have a relatively large number of exits in a relatively short section of roadway. Currently, there are a total of 27 exits and entrances (two-directional total) in a distance of about three miles. This number will be reduced to a total of 14 exits and entrances to provide an improvement in traffic operations. Yet, in the tunnel portion of the project there will still be a total of 7 exits including three exits that will be compressed into a 4,100 foot long southbound tunnel segment. Although the new tunnel will be an improvement over the existing Central Artery, there will still be a concentration of exits.

A further challenge is that Central Artery signing will guide the motorist to a large number of different "target" destinations. The current signing plan includes 14 target destinations that are signed in the southbound direction within the tunnel itself. These 14 include four "targets" beyond the tunnel to guide through traffic. The 14 target destinations are:

Exit 24 A-B *
An airport symbol for Logan Airport
A route shield for State Route 1A
Gov't Center *
1A NORTH *
A route shield for I-93, accompanied by SOUTH
A route shield for I-90
EXIT 22 *
South Station *
EXIT 23 *
Purchase Street *
SOUTH and a route shield for State Route 3
SOUTH and a route shield for U.S. Route 1
Quincy *

* denotes exact wording

The northbound tunnel has eight different target destinations. Clearly, there is a large amount of information to convey to the driver and a large amount of information for the driver to "filter" to determine which information is useful. Drivers will be searching for, and reading, this information at the same time as they are negotiating the horizontal curvature, executing lane changes, and dealing with heavy traffic, all within the confines of a tunnel environment. In other words, drivers will be subjected to an extremely high workload.

The above combination of conditions may mean that drivers – especially unfamiliar drivers – will have difficulty obtaining the guidance information they need to find the proper exit. This will lead to driver frustration and may also lead to a reduction in safety due to abrupt lane changing and other maneuvers. Other results will be a reduction in speeds and a possible reduction in throughput.

DRIVING SIMULATOR

To assess the current signing plan, the Driving Simulator at the University of Massachusetts (UMass) was used to replicate the driving experience through the Central Artery Tunnel. All of the geometric characteristics of the tunnel were re-created using Designer's Workbench ™

software. Tunnel height and width, horizontal and vertical curvature, lane placement, entrances, exits, and guide signing – in other words, all of the geometric and signing characteristics of the tunnel – were re-created for a simulated environment. This allowed the visual driving experience through the simulated environment to be a faithful replication of the driving experience as it will actually be when the tunnel is completed.

The fixed-base Driving Simulator at the UMass consists of a 1995 Saturn sedan dynamically linked to a Silicon Graphics Infinite Reality graphics engine. Figure 1 shows the Saturn and the three-screen, 150 degree field of view for a location within the Central Artery Tunnel. Drivers have control of the accelerator pedal, brake pedal, and the steering wheel, exactly like they do in a real automobile. Outputs from the car are used to determine what view of the scene is presented in the next frame. The scene is projected on three screens that provide a 150 degree field of view and the scene is refreshed 60 times per second. This interaction between the vehicle and the visual scene results in a simulation that appears very real. Data about driver position, velocity and brake pressure can be collected in real time, providing researchers the ability to collect meaningful data about driver performance in a variety of different driving situations.

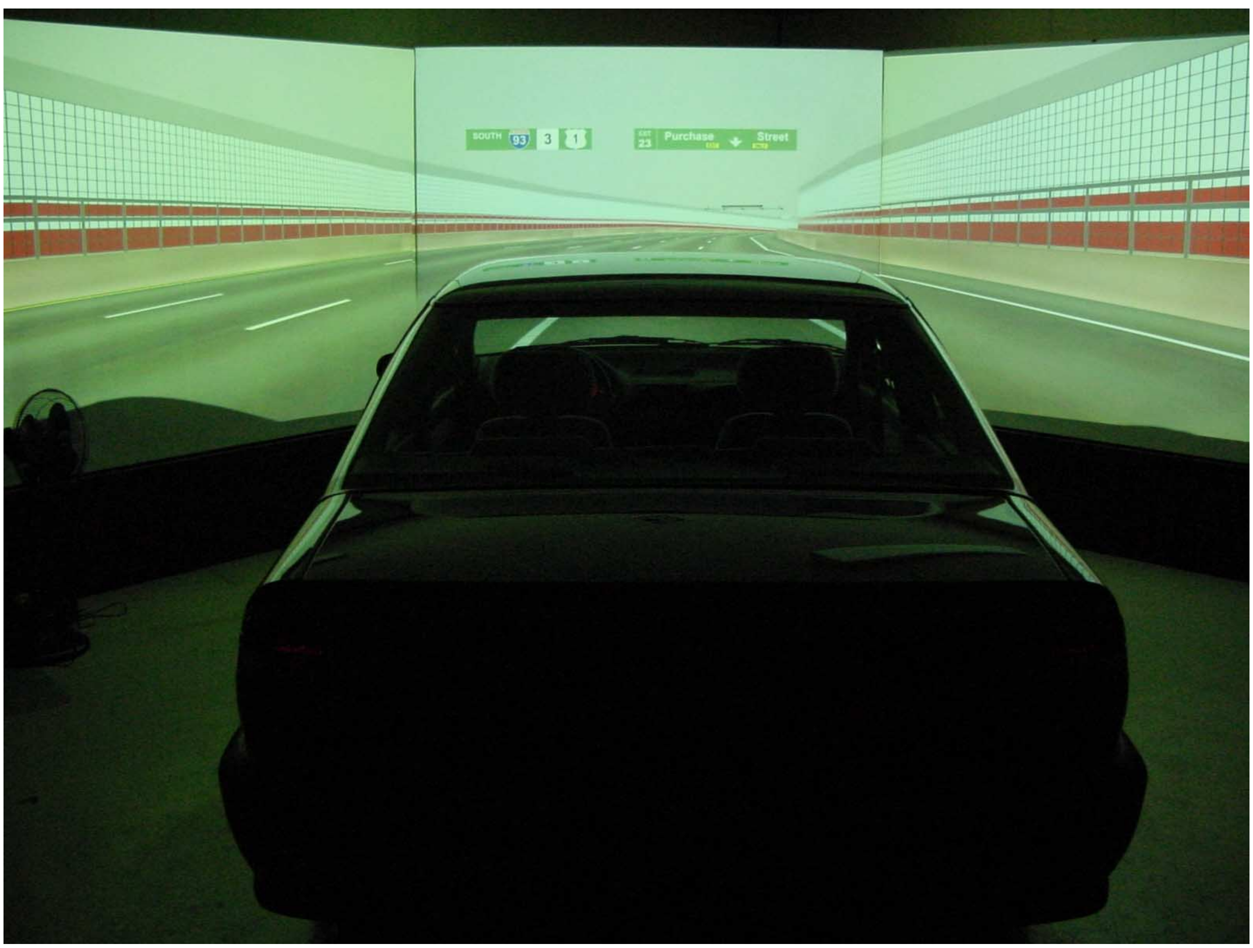


Figure 1 - UMass Driving Simulator

IDENTIFICATION OF SIGNING PROBLEMS AND POSSIBLE REMEDIES

After creating the visual database, including all tunnel elements, a series of steps was taken to identify possible signing problems and to create possible remedies. Those steps included the following.

> STEP 1. Members of the research team, experienced in highway signing and in human factors, drove through the virtual tunnel to look for signing situations that might be problematic. The roadway and signing plans on conventional plan sheets were also reviewed to identify possible problem areas. The drive through the virtual tunnel was particularly helpful in identifying locations where signs are obscured by horizontal and vertical tunnel geometry; these situations are not obvious when looking at two-dimensional plan sheets. Review of the signing plan allowed problematic situations – such as inadequate advance notice of an exit location – to be identified.
>
> STEP 2. Test subjects were recruited to drive through the tunnel in human factors experiments (an example experiment is described later). The experiments were designed to test whether certain signing situations are indeed problematic. Various Measures of Effectiveness were used for this assessment. Subjects were compensated for their time and participation.
>
> STEP 3. When a problem was confirmed through a human factors experiment, the research team, in consultation with tunnel and sign designers, identified potential solutions that were practical to implement.
>
> STEP 4. Potential solutions were implemented in the virtual environment and additional human factors experiments were run to determine the level of improvement offered by each solution.

Examples of problems identified in the STEP 1 review included:

> In most guide signing applications the first sign advising the driver of an exit or destination is usually placed at least one-half mile, and desirably one mile, in advance of the exit. The advance distance provides time for drivers to see the sign and read the message, and react to it (for example, by changing lanes) in time to execute an exit maneuver. Some exits had the first sign located as little as 1450 feet in advance of the exit. Other exits had the first sign at distances of 1760, 1800, 2800, 2950, 3550, or 3680 feet in advance of the exit.
>
> Due to horizontal and vertical curvature of the tunnel, some signs can not be seen until there is a very limited amount of viewing time available. One sign did not begin to become visible until a distance of 360 feet from the sign. This sign, for example would be visible for only about 2 seconds at 55 mph before it disappeared from view behind the

roof of the driver's vehicle. Another sign did not become visible until about 450 feet. A third sign was fully obscured at a distance of 600 feet.

Some guide signs are partially obscured (at some points upstream) by lane control signals or speed limit signs that are located a few hundred feet upstream from the guide signs.

An example of a STEP 2 human factors experiment will be described in the following section.

Potential solutions were identified in STEP 3, including those listed below.

Addition of an initial interchange guide sign further upstream.

Use of interchange sequence signs to provide more advance notice to drivers of upcoming exits.

Relocation of guide signs to locations where they would be less obscured by tunnel walls or ceilings (due to horizontal or vertical geometry).

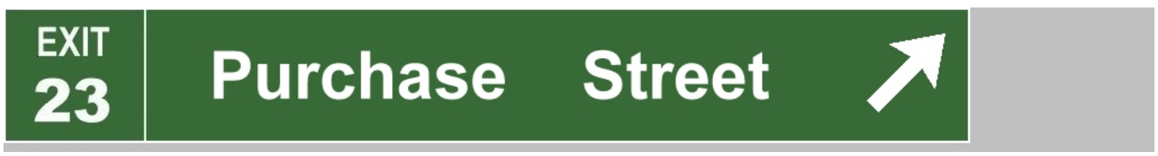
Redesign of guide signs to more clearly communicate information to the motorist.

HUMAN FACTORS EXPERIMENT – PURCHASE STREET SIGNING

Multiple human factors experiments were conducted in the driving simulator. An evaluation of the signing for the Purchase Street exit will be presented in this paper as an example of those human factors experiments..

STEP 1 analyses indicated that the Purchase Street group of exit signs may be more heavily obstructed than other target destinations. These problems are exacerbated by the existence of horizontal curvature immediately before the exit and the existence of an entrance ramp just before the exit ramp, with entering traffic weaving across the path of exiting traffic.

There are three signs which contain information on the Purchase Street destination, located 1450 feet before the gore (the legend is Purchase Street 1/4 Mile), 526 feet before the gore (the legend is Purchase Street Exit Only), and 49 feet beyond the gore (the legend is Purchase Street with a diagonal upward arrow). The three signs are illustrated below.



The second sign is difficult to see by itself since it is blocked by horizontal curvature to the right. This horizontal curvature, when combined with a truck immediately in front of the driver, makes it even more difficult to see this sign. The third sign is difficult to see by itself because it is located over the exit ramp rather than over the through lanes. Again, the visibility of the third sign is made especially poor when there is a truck in front of the driver.

Given the above problems, it was decided to test on the driving simulator whether test subjects would see the sequence of Purchase Street signs in time to safely to exit the mainline.

<u>Experimental Design</u>

It was hypothesized that the visibility of each sign would vary as a function of the lane in which the driver was located, the distance from the driver to a truck in the right lane which was placed in front of the driver, and the cognitive demands on the driver. In order to determine the effect of these three factors on driver performance, the following factors were varied:

a) the driver's lane – right (noted as *R*) or right center (*RC* - the lane adjacent to the right lane);
b) the distance of the truck positioned in the right lane in front of the driver – 60 (*60*) feet when the driver was either in the right or right center lane or 120 feet (*120*) when the driver was either in the right or right center lane; and
c) the cognitive demands on the driver. The driver workload was varied by either presenting, or not presenting, the first of the three Purchase Street exit signs. The

absence of the first Purchase Street sign was designed to represent the situation in which a driver does not notice this sign due to heavy workload or distraction while driving. The situation where the first Purchase Street sign was present is referred to as the *Easy* condition. The situation where this sign was absent is referred to as the *Hard* condition.

The right or right center lane for the driver and the right lane for the truck were chosen because those combinations appeared to obscure the Purchase Street exit signs the most. The truck was placed either 60 or 120 feet in front of the driver because these constituted possible worst case scenarios. And finally, the decision to either present or not present the first Purchase Street sign was made because it could well happen that drivers, overloaded by demands on their attention, do not see one of the signs. Not seeing the first sign in this case is arguably the worst situation, at least from the standpoint of traffic flow and incident control, since in this case the driver must make the exit decision with very little advance warning.

<u>Procedure</u>

Twenty-four test subjects participated in this experiment. Participants were told before the beginning of the experiment to exit at Purchase Street. They were not given any practice runs through the tunnel before the experimental trial, thus they were not familiar with the exit sign sequence. We recorded the number of missed or late exits, as well as both the position at which they first decided to change lanes and the position at which they moved onto the exit ramp. A missed exit means that the driver did not exit at Purchase Street. A late exit means that the driver moved from the right hand lane to the exit ramp at or beyond the gore point.

<u>Results showing types of errors made by test subjects</u>

Results are presented here in two forms. The first set of results is categorical and is summarized in the table below:

Driver Behavior	Number	Number: Condition
Missed Exit	3	2: RC/60/Hard,1: RC/120/Hard
Late Exit	2	1: RC/60/Easy,1: RC/60/Hard
Double Lane Change	3	2: RC/60/Easy,1: RC/120/Hard

Three out of 24 test subjects completely missed the exit. The conditions under which these missed exits occurred were as follows. Two of these drivers started in the right center lane (RC) with the truck 60 feet ahead of them in the right lane (60). The first Purchase Street sign was not present in the simulation (Hard). One of the drivers who missed the exit also started in the right center lane and also did not have the benefit of being presented the first Purchase Street sign. However, in this case the truck was positioned in the right lane 120 feet ahead of the driver.

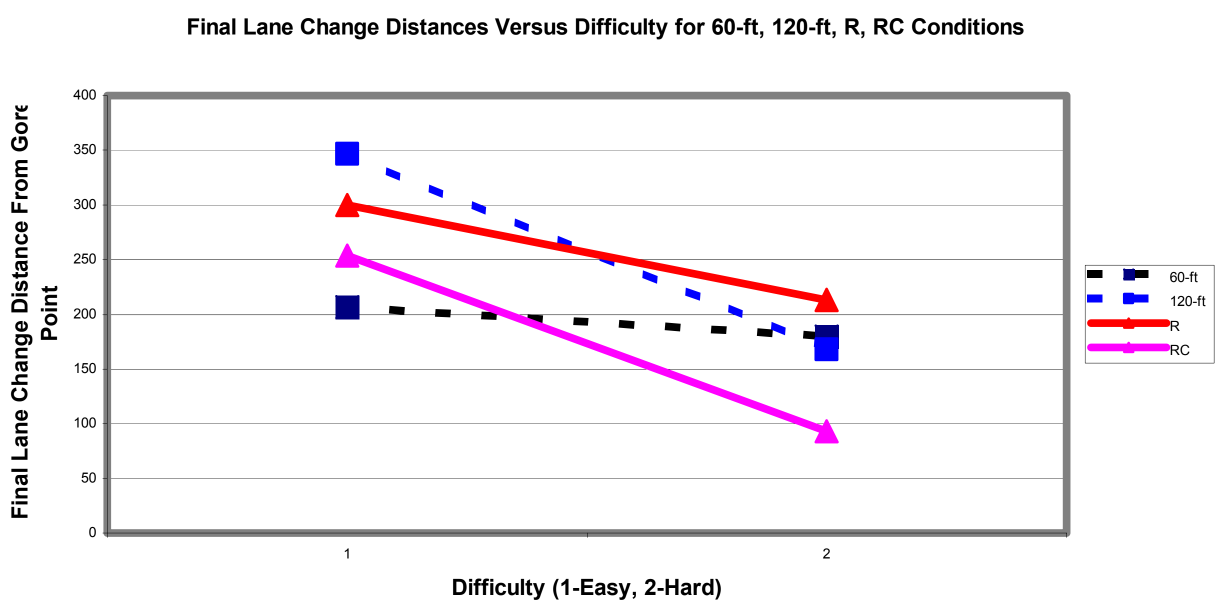
Two drivers were late exiting. One actually turned into the exit ramp 40 feet after the gore point (RC/60/Easy). The other turned into the exit ramp right at the gore point.

Finally, three drivers who started in the right center lane engaged in a double lane change maneuver to make the exit. This is a dangerous maneuver because the two lane changes were continuous and occurred relatively close to the exit. It is true that all drivers in the right center lane will need to change lanes twice. But, it is not generally the case that they combine these two lane changes into one larger double lane change.

All of the above errors are attributed to the fact that signing is not easily seen due to the horizontal and vertical curvature of the tunnel and obstruction by large trucks.

Results showing the longitudinal location of the final lane change

The second set of results summarizes the longitudinal point at which a final lane change was made by drivers. Specifically, the number of feet in advance of the Purchase Street gore point at which the final lane change was made was recorded. The further upstream from the gore the driver initiates this lane change, the more time the driver has to make that change if the exiting lane is blocked by vehicles entering the freeway at that point:



The results show distinct differences, depending upon the lane in which the driver is located and the distance from the driver's vehicle to a preceding truck. First, consider the effect of the lane in which the driver's vehicle is located (solid red and pink lines). If the driver is in the right hand lane and all three Purchase Street signs are presented, the final lane change is made a full 50 feet sooner than if the driver were in the right center lane. 50 feet sooner corresponds to about 0.7 seconds sooner. However, if only the last two Purchase Street signs are presented, then drivers in the right lane make the change a full 125 feet sooner than do drivers in the right center lane. 125 feet sooner corresponds to about 1.7 seconds sooner. This clearly demonstrates the importance of drivers being able to see the guide signs.

Second, consider the effect of the distance of the truck ahead of the driver (dashed black and blue lines). Clear effects of this distance are apparent when all three signs are present. In fact, when all three signs are present and the truck is a full 120 feet ahead of the driver, the drivers change lanes 150 feet sooner than they do when the truck is only 60 feet ahead of them. Our interpretation is that this clearly shows that a truck can block out a sign and prevent a driver from seeing the sign. When the first of the three Purchase Street signs is not present, the distance of the truck from the driver does not make a difference. In particular, even when a full 120 feet separates the driver and the truck, the drivers perform no better than they would if only 60 feet separated them from the truck ahead. Essentially, without the first of the three Purchase Street signs, they do not have enough warning that the exit is coming up.

Finally, consider the effect that the presence of the first Purchase Street sign has on the performance of drivers. On average, drivers exit about 125 feet earlier if that sign is present. This suggests that Advance Guidance signs could help considerably when the cognitive load is high, as it will be in the tunnel.

CONCLUSION

The driving simulator had great utility for evaluating possible problems with guide signing for the Central Artery Tunnel. This tool allowed not only the identification and confirmation of problems, but also an evaluation of candidate remedies, both through human factors experiments. This study will result in improved signing for the Central Artery Tunnel.

A driving simulator was particularly useful on this very complex highway design. The horizontal and vertical curvature, restricted tunnel height, sign size and location, etc. could be faithfully reproduced in a simulation. A simulated drive allowed both researchers and sign designers to observe problems that were not so obvious on two-dimensional plan sheets. The driving simulator has also been very useful in situations with equally severe, though somewhat different, constraints on curvature of the roadway, placement of the signs, and density of the information that must be displayed on the signs such as Logan International Airport (1). Although most projects are much simpler in their design than the two mentioned immediately above, this approach will undoubtedly be very useful on many future projects.

REFERENCES

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