

**A Study of Alternative Drive Control Interfaces for Next-Generation**

**Electric Vehicles**

by

C. Christopher Post

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Submitted to the Department of Electrical Engineering and Computer Science  
in Partial Fulfillment of the Requirements for the Degree of  
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## **Abstract**

The drive control interface in automobiles has not significantly changed for almost a century. Recent advances in electric vehicles and drive-by-wire technology allow for new alternative interfaces that enable novel vehicle designs. This study examines alternative driving interfaces by prototyping controls for use with a driving simulator. Volunteers use these interfaces to drive simulated scenarios designed to isolate specific interface features that are intuitive and easy to use. These results are used to inform the design of a new interface which is also tested with the simulator. The simulation results are used to identify design elements of successful alternative driving interfaces.



## Acknowledgements

I would like to dedicate this work to the memory of Bill Mitchell. His dynamic personality and unparalleled enthusiasm for the future of urban mobility instantly drew me into the CityCar project. It was easy to see his passion for the research; he wanted to make cities cleaner, safer, and more effective for everyone. I consider myself very lucky to have had the opportunity to work with him, and he will be remembered always.

This work would also not be possible without the direction of Kent Larson, who courageously stepped in to ensure the continued success of the CityCar. Kent has been an invaluable resource for ideas and experimental design throughout the course of this study. The CityCar project as it exists today would certainly not be possible without him.

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For their patience and willingness to participate, I would like to thank the volunteer drivers. Their help supplied me with key insights and observations throughout the process of designing and testing these interfaces.

Last, but certainly not least, I would like to thank my parents for their love and support throughout my entire academic career. None of this would be possible without them.



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# 1 Introduction

Every commercially available automobile today is equipped with the same interface for drive control: a steering wheel and pedals. While this is an interface that all drivers are familiar with, developments in automotive drive-by-wire technology open up possibilities for driving a car via almost any physical interface imaginable. In this thesis, I show that there are compelling reasons to investigate alternatives to the conventional driving interface. In particular, the CityCar is a unique vehicle that requires a nonconventional driving interface. I prototype alternative driving interfaces and integrate them into a computer driving simulation with several courses specifically designed to test individual performance characteristics of each driving interface. Volunteers drive the simulator using these custom driving interfaces, and the simulation results are analyzed to produce interface performance metrics that are used to compare the relative usability of each interface. Using these results, I revise the most successful alternative interface with the goal of achieving similar performance to a conventional steering wheel and perform another round of comparison testing. Collectively, the performance metrics, subjective observations, and driver feedback give rise to a set of design principles and guidelines that can be used to influence the development of alternative driving interfaces.

## 1.1 History

Since the very earliest days of the automobile, a drive control interface consisting of a steering wheel and pedals has been common to almost every car. Although the steering wheels of today are quite different from their ancestors, the basic principle of operation has not significantly changed in the last century. Originally, the steering wheel was an ideal driving interface because all mechanical power for turning the wheels had to originate from the driver. A large steering wheel enabled the driver to easily apply enough power to turn the wheels. It also allowed for a large range of motion while still keeping effort low since the steering wheel can be turned multiple times in each direction to apply maximum steer to the wheels.

Later, the advent of power steering enabled power from the engine to be transferred to the steering column when needed, greatly reducing the power required from the driver. As a result, steering wheels started becoming smaller and less obtrusive. The steering wheel's basic design, though, has not changed because it is still connected mechanically to the wheels, constraining the possible design options for a driving interface.

## **1.2 Drive-by-Wire**

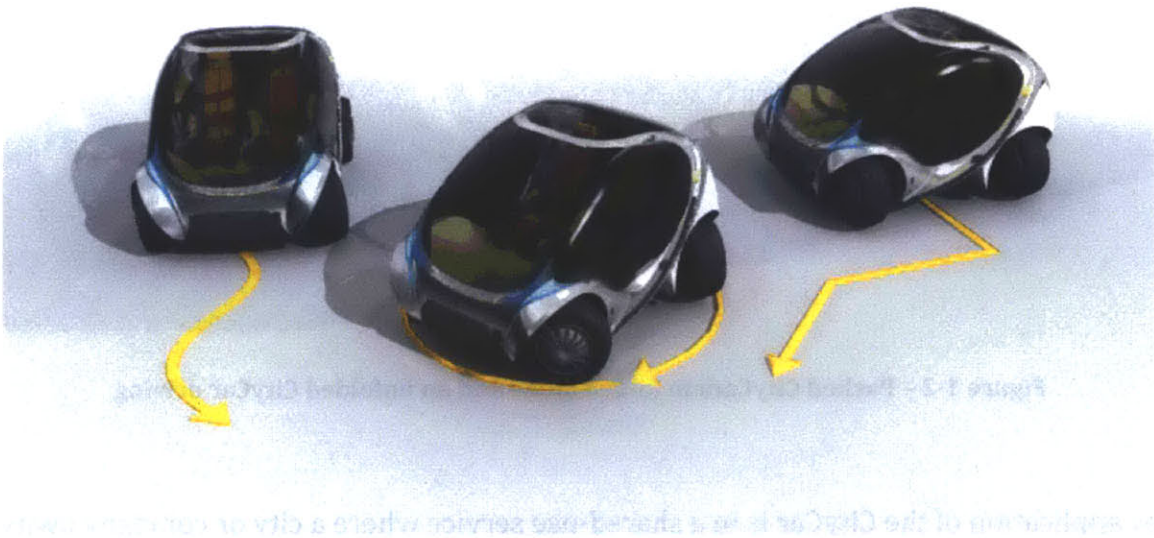
Over time, the automotive industry has revised an increasing amount of car subsystems to use digital networking instead of mechanical or analog electronic linkages. In the 1980's, Bosch developed the Controller Area Network (CAN) specification, which has been one of the most widely used communication busses in vehicle networks. A vehicle-wide communications network enables many electronic subsystems (such as climate control, seat adjustment, windows, and locks) to interact easily without point-to-point wiring for every subsystem. Despite its convenience for integrating multiple subsystems, CAN is only well suited to tasks that are not safety-critical.

As more and more vehicle subsystems move into the electronically-networked domain, it is a natural evolution for the automotive industry to begin moving safety-critical driving control subsystems away from the mechanical and into the networked electrical domain. This trend has resulted in the exploration of "drive-by-wire" systems, which are intended to replace the traditional mechanical systems for steering, braking, and throttle.

With drive-by-wire systems, mechanical constraints that previously coupled the driving interface input to the car's output are removed. The steering interface no longer needs to provide direct power to the wheels; an actuator converts software commands from the steering interface into mechanical actions. This allows for many possibilities of physical driving interfaces and software flexibility for quickly changing interface parameters.

### 1.3 CityCar

The CityCar project aims to create an electric vehicle designed for easy mobility in dense urban environments. It holds two passengers and has the ability to fold when parked, greatly reducing its parking footprint; this is a valuable feature in cities since parking space is a scarce resource. The CityCar also utilizes drive-by-wire technology to enable unique driving behaviors to add maneuverability that would not be possible with a traditional automobile drivetrain. Each wheel has an independent motor located in the wheel itself, and each wheel is independently steerable. This allows the car to turn its wheels inwards and spin on its center using a zero-radius turn or translate laterally (Figure 1-1) to fit into parking spaces that would be too small for a car with traditional steering. See [2] for further discussion of the CityCar.



**Figure 1-1 - The CityCar using conventional steering (left), zero-radius steering (middle), and translation (right)**

Another unique feature of the CityCar is the front door, which allows both passengers to enter and exit the vehicle through the front instead of the sides. This, combined with the zero-turn radius mode, permits the CityCar to park facing the curb as shown in Figure 1-2, allowing passengers to step safely out onto the curb instead of into the street. This feature

directly influences the design of a driving interface for the CityCar since the driver must be able to have an unobstructed path to enter and exit the car through the front. A traditional steering wheel and pedal set is not an ideal driving interface for the CityCar since it occupies a significant amount of space in front of the driver. If possible, pedals should not be used in the CityCar to keep the floor in front of the driver free of obstacles to entry/exit, and the driver should be able to exit the seat without interference from the driving interface. Consequently, the alternative driving interfaces explored in this thesis focus on designs where the driver's hands operate all driving functions. Suitable designs for a CityCar driving interface must also keep the entry/exit path completely clear or be able to easily swing out of the way to allow the driver to pass.



**Figure 1-2 – Parked CityCars in folded mode and an unfolded CityCar driving**

A key application of the CityCar is in a shared-use service where a city or company owns and maintains a fleet of cars that can be rented by members of the service. This helps reduce overall traffic congestion and need for parking spaces within cities, since a shared-use system enables higher utilization of cars within the city than if all cars are personally owned. The shared-use scenario is another important consideration in the design of a CityCar driving interface. Some alternative driving interfaces may have a steep learning curve and become easy to use after the driver has had significant experience with the

interface but be very difficult to learn initially. An ideal driving interface for the CityCar must be easily useable by drivers with little experience on the interface.

## **2 Previous Work**

Currently, there are no commercially available vehicles that use alternative driving controls, but some alternative driving interfaces have been developed for concept vehicles. Each interface has unique features, but they can be generally divided into two broad categories: yoke and joystick controls. Yoke controls rely on rotation in the same plane as a conventional wheel and use upper and lower arm motions for steering, but usually do not allow multiple revolutions and only allow the driver's hands to grip the interface in specific positions instead of any point around the wheel. Joystick controls rely on side-to-side tilt and primarily use wrist motion for steering.

### **2.1 Yoke**

In 2010, General Motors unveiled the EN-V, a small personal mobility vehicle. The EN-V uses a small yoke that can fold into a space between the seats when not in use (Figure 2-1). A design such as this is of particular interest for the CityCar project, as the driver must be able to exit through the front, much like the EN-V. The driver rotates the yoke to steer, pushes the yoke forward to accelerate, and pulls the yoke back to brake. Prior to this, GM was developing a concept hydrogen fuel cell car, the Hy-wire, that also uses a yoke interface (Figure 2-2). The Hy-wire uses a different approach for throttle and braking where twisting the handles controlled throttle and braking.



**Figure 2-1 - Cockpit and control yoke for the EN-V [3]**



**Figure 2-2 - Yoke control in the Hy-wire [5]**



## 2.2 Joystick

In 1996, Mercedes-Benz displayed the F 200 concept car, which used a centrally located joystick to operate steering, braking, and throttle (Figure 2-3). It did not ever enter production, but was one of the first joystick-operated concept cars. A more recent example is the dual-joystick strategy used in Toyota's FT-EV II concept vehicle (Figure 2-4) where the driver uses both hands to control the car. Both these systems use left and right motions on the joystick to steer; forward and back motions operate the throttle and brake.

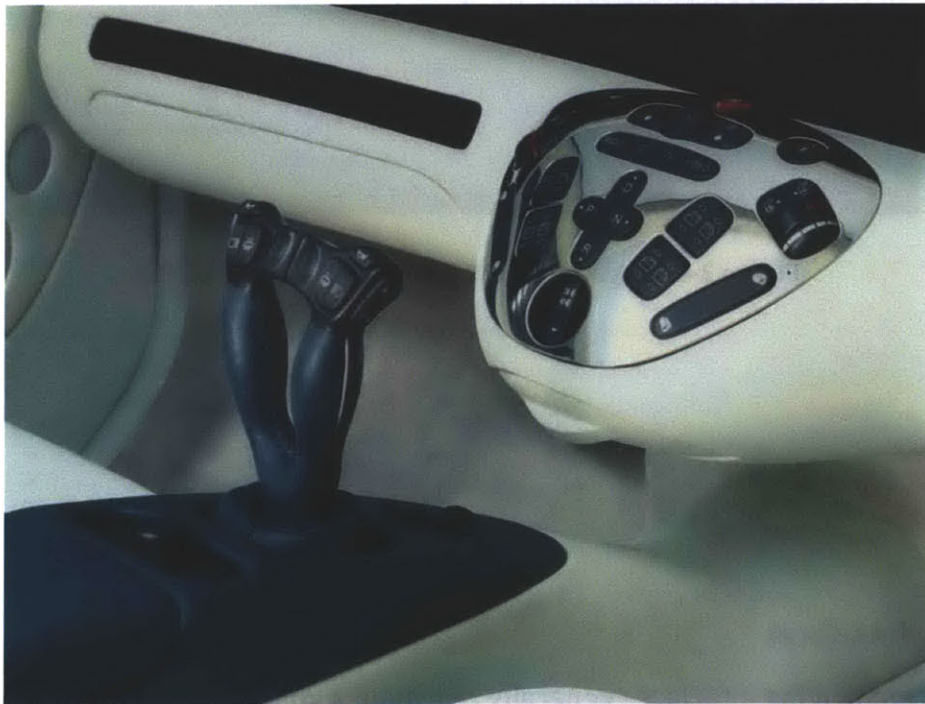


Figure 2-3 - Mercedes-Benz F 200 central joystick interface [4]



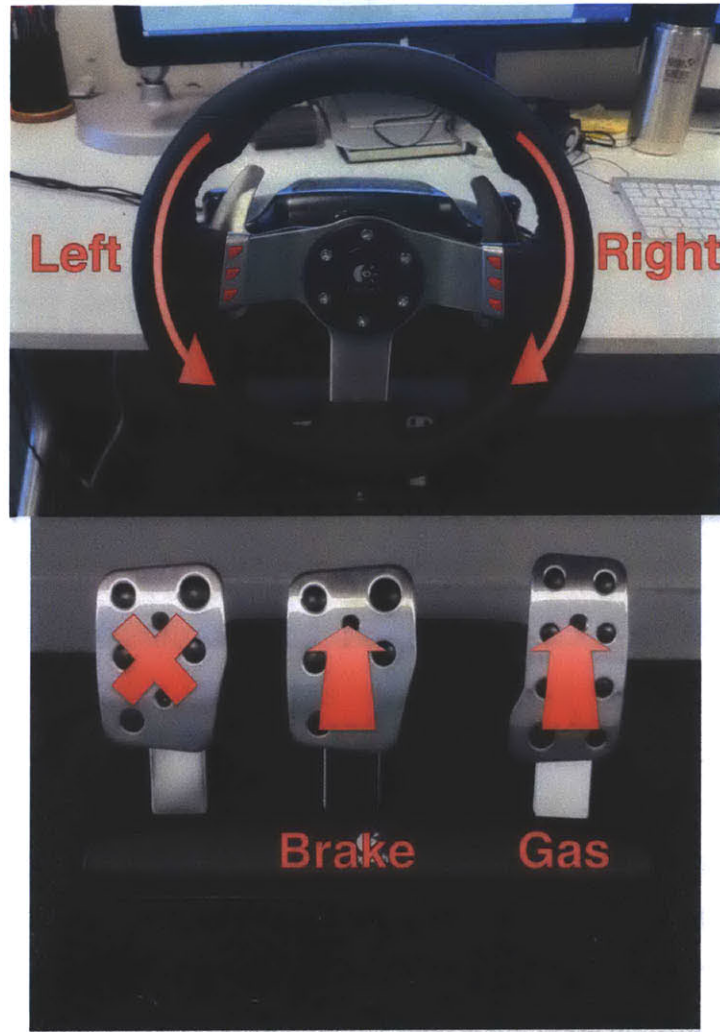
**Figure 2-4 - Toyota FT-EV II dual-joystick interface [1]**

### **3 Simulator Design**

#### **3.1 Driving Interfaces**

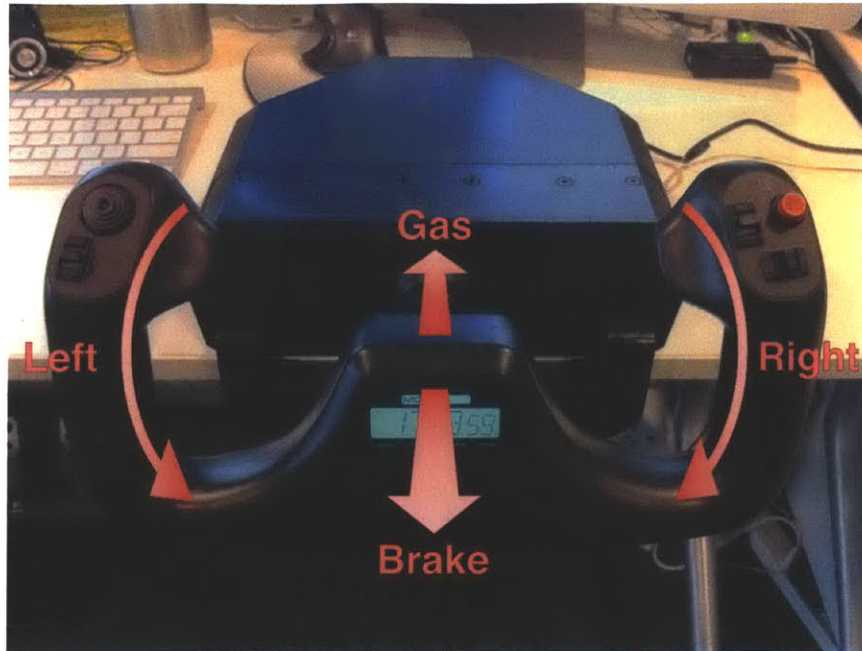
Existing concept driving interfaces generally resemble a yoke or a joystick assembly. Since these are the two broad categories of potential driving interface designs other than the steering wheel, comparison among a steering wheel, yoke, and joystick interfaces is the focus of the driving simulator.

A conventional steering wheel and pedals (Figure 3-1) is used as a baseline for comparison, since drivers are already familiar with this interface. This steering wheel has force-feedback motors that push the steering wheel based on simulated forces from the car's wheels. Thus, this interface responds very much like a conventional car.



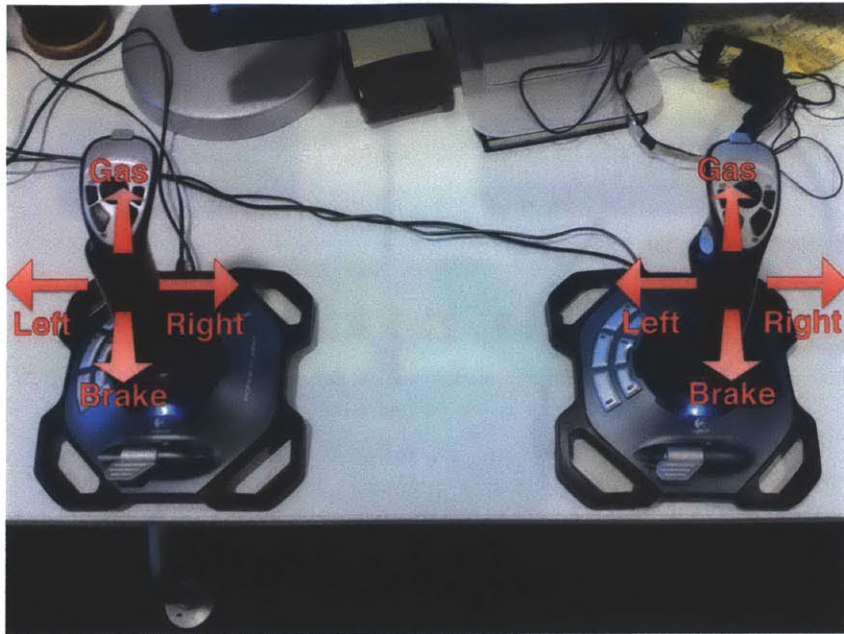
**Figure 3-1 - Operation of the steering wheel and pedals**

For a yoke control, a flight simulator yoke is used (Figure 3-2). The yoke does not have force-feedback and uses a simple spring return mechanism for steering. The second axis is in the direction facing directly forward away from the driver, so the driver can push and pull on the yoke as well as steer. The push/pull also has a simple spring return mechanism. The yoke is designed to use a push motion as applying throttle to the car and a pull motion to apply brake since this is the most obvious motion mapping that corresponds to the car's movement.



**Figure 3-2 - Operation of the push/pull yoke interface**

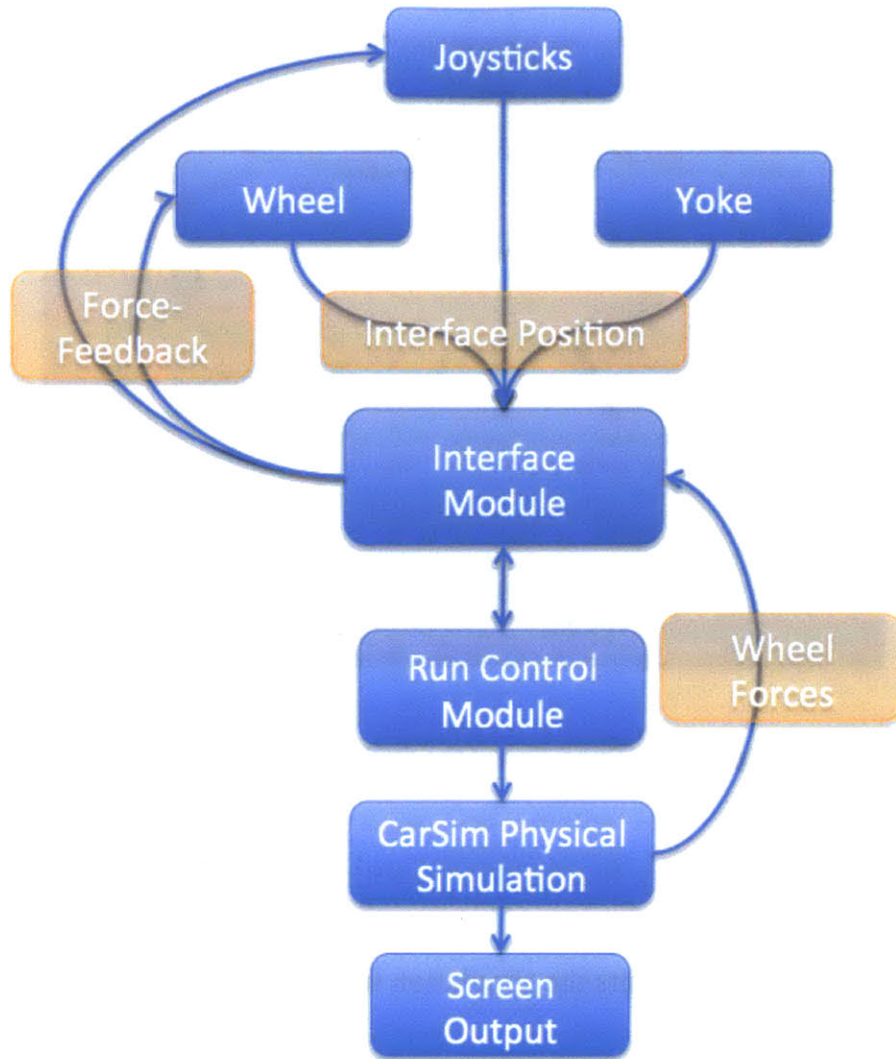
The joystick interface uses two joysticks (one for each hand) that are synchronized through force-feedback (Figure 3-3). Two joysticks are chosen because it is likely that only having one joystick to control a car would result in excessive fatigue during longer driving sessions. On a conventional steering wheel, the driver is free to switch hands without any interruption in drive control. With two joysticks, the driver may use either hand or both if desired. The joysticks are synchronized in software to use the force-feedback mechanism so that each joystick follows the motion of the other, keeping the driver from getting confused if the joysticks are in conflicting position and making the task of deciding the “correct” output behavior for the drive-by-wire system easier if the positions of the two joysticks do happen to conflict by some amount.



**Figure 3-3 - Operation of the dual-joystick interface**

### **3.2 Simulator Architecture**

The CityCar driving simulator splits the simulation functions into the modules described in Figure 3-4.



**Figure 3-4 - Simulator block diagram**

### 3.2.1 Physical Simulation

The driving simulator utilizes CarSim, a vehicle dynamics simulation engine, to run math models that compute the car’s behavior based on control inputs. The CityCar’s kinematic parameters are modeled in CarSim to produce a simulated car that performs much like a full-size CityCar. Since the CityCar is a unique vehicle with its in-wheel hub motors and independently-steerable wheels, it may handle differently than a standard car, so this

accurate representation allows the alternative interfaces under test to be uniquely tailored to the CityCar's particular behavior.

### **3.2.2 Run Control Module**

The run control module is responsible for invoking the physical simulation, gathering data from the driving interface inputs, and calculating the behavior of the wheel robots. Since the CityCar wheel robots are a unique drivetrain configuration that the CarSim engine does not support, the run control module overrides CarSim's internal drivetrain model and supplies individual wheel torque values to the physical simulation engine based on electric motor models calculated by the run control module. This module is also responsible for calculating the torque to supply to the steering actuator for each wheel for the CityCar's independent steering.

### **3.2.3 Interface Module**

The interface module interacts with the physical driving interfaces over USB to acquire the interface's input position. It then translates the interface's position into a normalized control input for the robot wheel models. For the steering wheel, the interface module also receives force on the car's wheels from the physical simulation, combines and scales the values based on what steering mode the car is in (four-wheel or two-wheel), and outputs a force to the steering wheel. This enables the driver to feel the wheels as they contact the road, like a mechanical driving interface. The interface module also outputs force-feedback for the joysticks, but has the additional task of synchronizing the joysticks. To do this, the interface module calculates the position difference between the two joysticks and uses this as an input to tuned PID (proportional-integral-derivative) controllers for each joystick that send force outputs to the joysticks that pulls the joysticks back into alignment with each other. If the driver is holding only one joystick, the other joystick will move in synchrony. This prevents unintuitive behavior where the joysticks are being moved in opposite directions, since they will resist the driver if the driver attempts to forcefully do so. With both hands on the joysticks, the force from the synchronization process naturally keeps the driver's hands moving together.

### **3.3 Testing Procedure**

The driver performs a series of testing courses in the simulator as described below for each of the three interfaces. The order that the driving interfaces are presented to each driver is permuted across drivers such that each interface has equal time being placed in the beginning, middle, and end a driver's testing session. Since the CityCar's shared-use scenario is an important consideration, the driver's only instruction on how to use each interface is a printed diagram of the interface so that the learning curve difficulty for an interface can be determined as the driver becomes familiar with the interface throughout the test.

The individual driving tests are conducted in the same order for each interface to allow the driver to become familiar with the interface at the beginning before moving on to more demanding tests. For all driving tests, the control inputs and all simulation parameters required to reproduce the test are recorded so that the test may be replayed in its entirety.

#### **3.3.1 Introductory Road Course**

The first driving test is a short road course with turns of varying sharpness. The driver is instructed to complete the course at a leisurely pace as if the driver were in a real car on the same road. The driver is also instructed that staying in the right lane of the course is the top priority. This course should take a few minutes to complete, but the participant is made aware that time is not important. The layout of the course is shown in Figure 3-5.





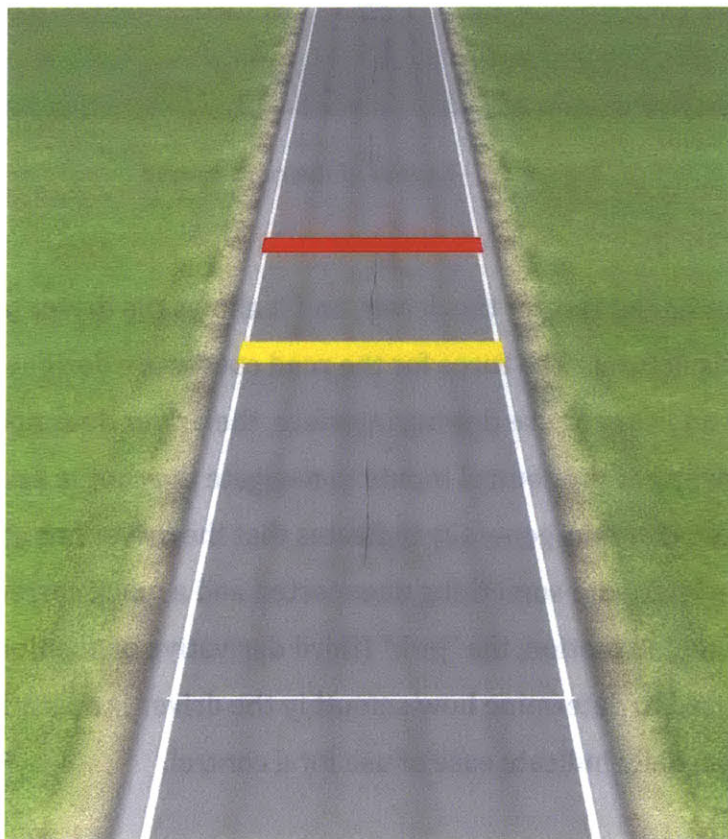
**Figure 3-5 - Layout of the road course**

This is the most open-ended test for the driver, and it allows the driver to use the interface in whatever way feels natural. The turns for the road course are designed to be smooth so that, for an intuitive and easy to use driving interface, the driver does not need to make sudden motions with any of the control inputs to navigate the course easily. Sudden motion in steering, for example, generally indicates that the driver has encountered a time where the driving interface did something unexpected and a quick correction must be made. To measure sudden motion, the “jerk” (third derivative of position) of the control inputs over time is used to determine how smoothly the driver is operating a particular control, which will partially indicate ease of use for a control.

### **3.3.2 Acceleration/Braking**

This test isolates the throttle and braking controls apart from steering. On a straight track, the driver is asked to accelerate as steadily as possible (linear in velocity) to a

predetermined top speed such that the car reaches the top speed as soon as it crosses yellow line marked on the track, as shown in Figure 3-6. The driver is also instructed to begin slowing down steadily once the car crosses the yellow line such that the car stops on the red line. The driver is shown a printed version of Figure 3-6 along with the instructions. The lines and top speed are designed such that the participant must maintain a throttle and brake position less than full in order to achieve a linear speed change through both sections. A speed change in the first section that is very close to linear indicates that the driver finds the throttle easy to use, and a linear speed change in the second section indicates that the driver finds the brake easy to use. To identify if there is a difference in usability at different speeds, the driver has one attempt at a course designed for a 40km/h top speed and one attempt on a course designed for a 60km/h top speed.



**Figure 3-6 - Acceleration/Braking course layout for 40km/h top speed**

### 3.3.3 Slalom

The slalom course is used to isolate how easy it is for the driver to use an interface's steering control. The slalom course (shown in Figure 3-7) consists of evenly spaced cones that the driver must alternately pass on the left and the right, weaving in between the cones. The driver is instructed to accelerate to and maintain a constant speed before entering the slalom course. The speed and spacing of the slalom course is designed such that it is comfortably navigable with the CityCar's handling capability for the given speed. For a very intuitive interface, the driver should be able to operate the steering smoothly. Thus, the jerk of the steering inputs can be compared among various interfaces for a measure of relative steering usability. The driver has one attempt at a course designed for 30km/h and one attempt at a course designed for 50km/h.

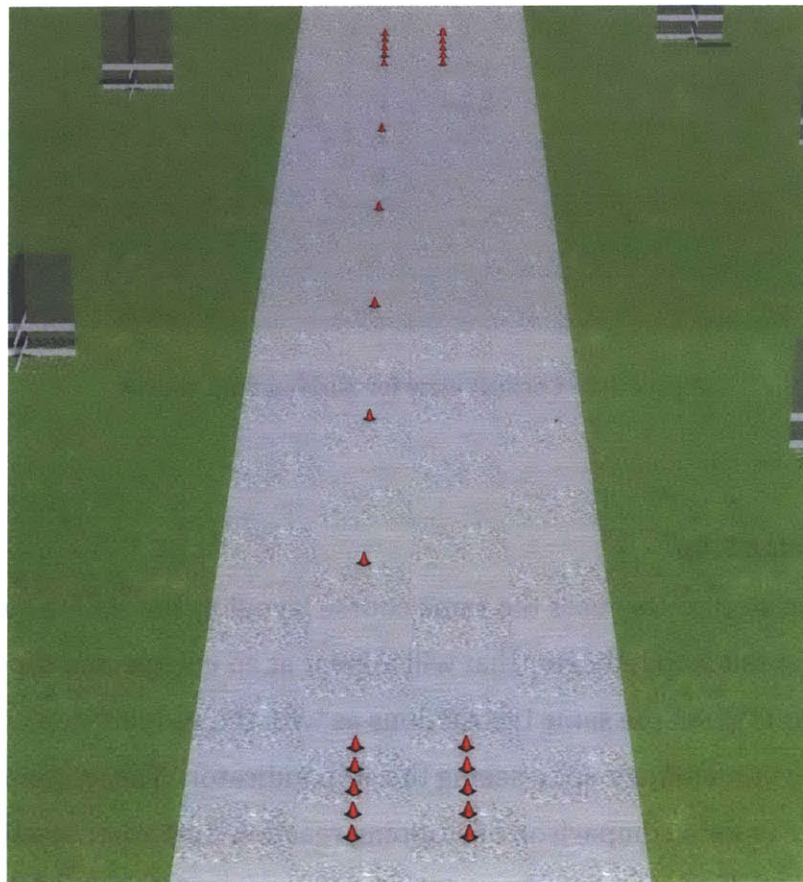


Figure 3-7 - Slalom course layout for 30km/h speed

### 3.3.4 Sudden Stop

For the sudden stop course, the driver is instructed to reach a speed of 40km/h and drive straight down the road. The driver is told that a large red stop indicator will suddenly appear in the road at some point, but not when the stop indicator will appear. The driver should stop as fast as possible when the stop indicator appears. The reaction time between the indicator appearing and when the driver applies brakes is measured to allow comparison of braking usability during a sudden stop scenario.

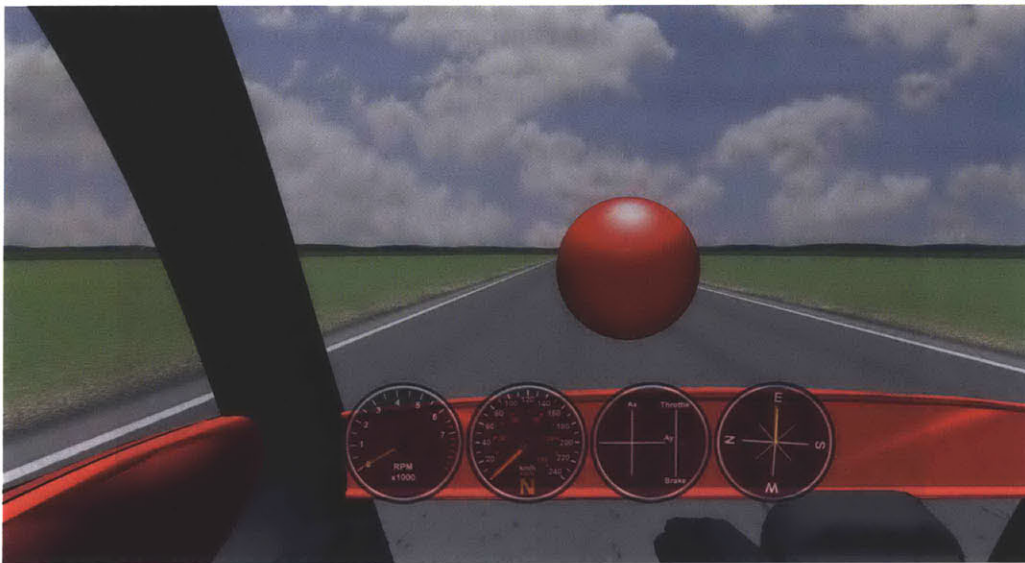


Figure 3-8 - Cockpit view for Sudden Stop course

### 3.3.5 Slalom Sudden Stop

The slalom sudden stop course uses the same course layout as the slalom course in Figure 3-7, but in addition red stop indicator that will appear at an unexpected time during the course. The driver is given the same instructions as with the sudden stop course; the driver should stop immediately upon seeing the stop indicator. The stopping reaction time on this course allows for a comparison of stopping reaction time when the driver is distracted with the task of steering. On an interface where steering interferes with braking, the reaction time will be much longer.

### 3.3.6 Lane Toss

The lane toss course consists of three lanes of cones with a gap where the participant may change lanes without knocking over any cones. The driver is asked to reach and maintain a pre-set constant speed (40km/h) up until the end of the first section of cones. As the driver exits the first section of cones, lights above one of the three lanes in the next section will light to indicate which lane the participant move into. This tests how intuitive the steering control is in the face of split-second judgment calls. The ideal path given the car's handling is compared to the actual line that the participant takes to change into the new lane. Deviations from the ideal line are compared among various interfaces to determine relative usability of the steering control for quick maneuvers. The driver performs this test twice.

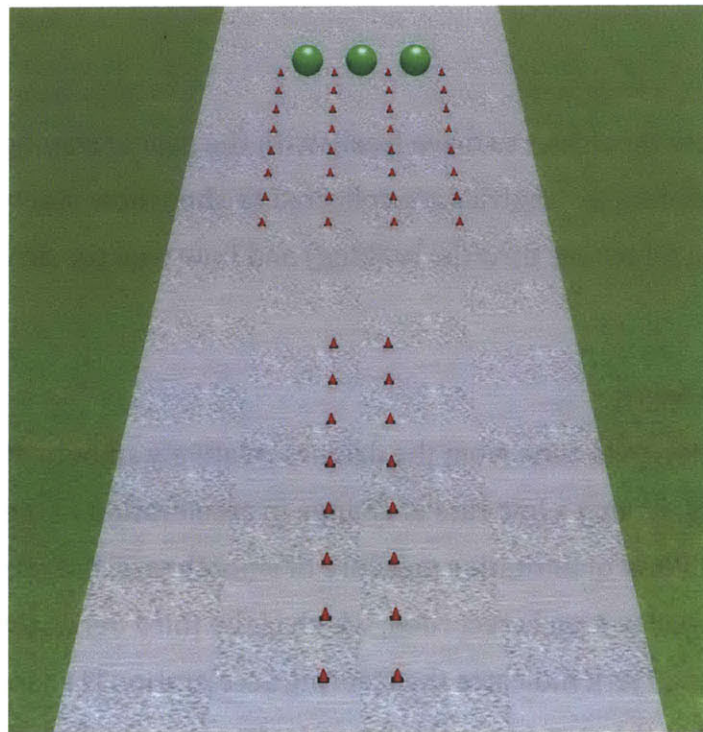


Figure 3-9 - Lane Toss course layout

### 3.3.7 Concluding Road Course

After the other tests for an interface, the driver performs a lap around the same road course as the introductory road course described in Section 3.3.1, except in this test the

course is driven in the opposite direction. Since the course is driven in reverse, the driver is not able to easily anticipate any upcoming elements in the course, so the driver is effectively driving on a course that has not been seen before. Since the course is the same, though, the metrics from the first road course can be applied here as well. These metrics are compared between the two road courses to obtain a measure of how familiar the interface has become to the driver during the other tests, indicating the interface's learning curve.

## **4 Initial Simulator Testing Results**

### **4.1 Road Course**

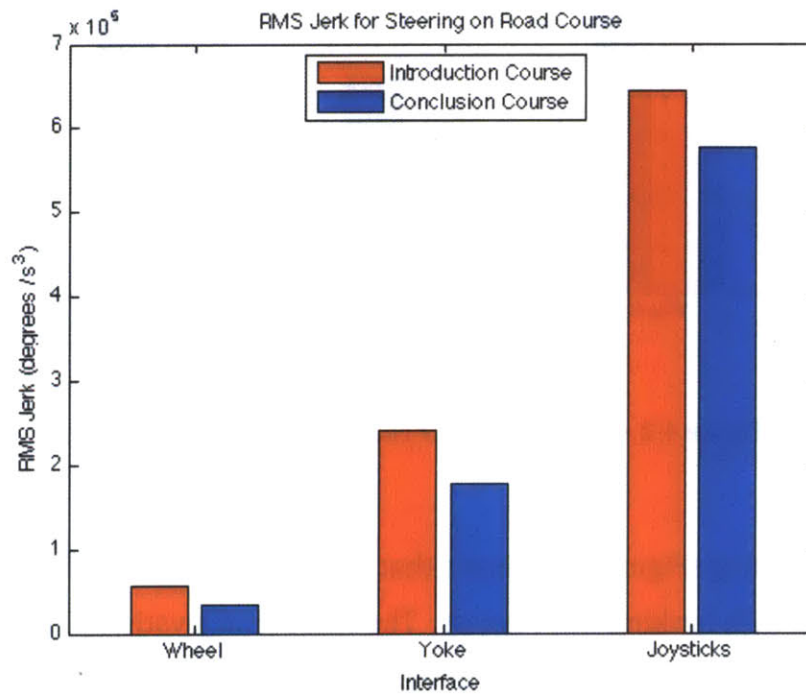
The road courses allow the driver to drive freely with the goal of staying in the right lane of the road. For the road courses, metrics are collected to show how smoothly the driver operates the interface (steering, throttle, braking) and how well the driver follows the lane.

#### **4.1.1 Control Smoothness**

If an interface's position over time from the drive is relatively smooth, its acceleration will not change drastically; having a low rate of change in acceleration of the interface indicates smoother operation. For a quantitative measure of smoothness, the rate of change of the steering interface's acceleration is recorded, which is the third derivative of position and known as "jerk." A small jerk indicates the steering acceleration is changing slowly, and a large jerk indicates that the steering acceleration is changing quickly. This quantity can be examined over time by using the root of the mean of the squares (RMS) of instantaneous jerk measurements. A small RMS jerk means the driver operates the interface smoothly, indicating that the interface is comfortable to use. If the driver finds an interface confusing, he will struggle with the interface, causing a large RMS jerk.

To compare the relative usability among the wheel, yoke, and joysticks, the RMS jerk for steering, throttle, and braking are compared. Since the driver performs the same road course both forward and backward at the beginning and end, respectively, of the tests for an interface, comparing the RMS jerk between the introduction and concluding road course gives a measure of how much the driver became comfortable with the interface throughout the tests.

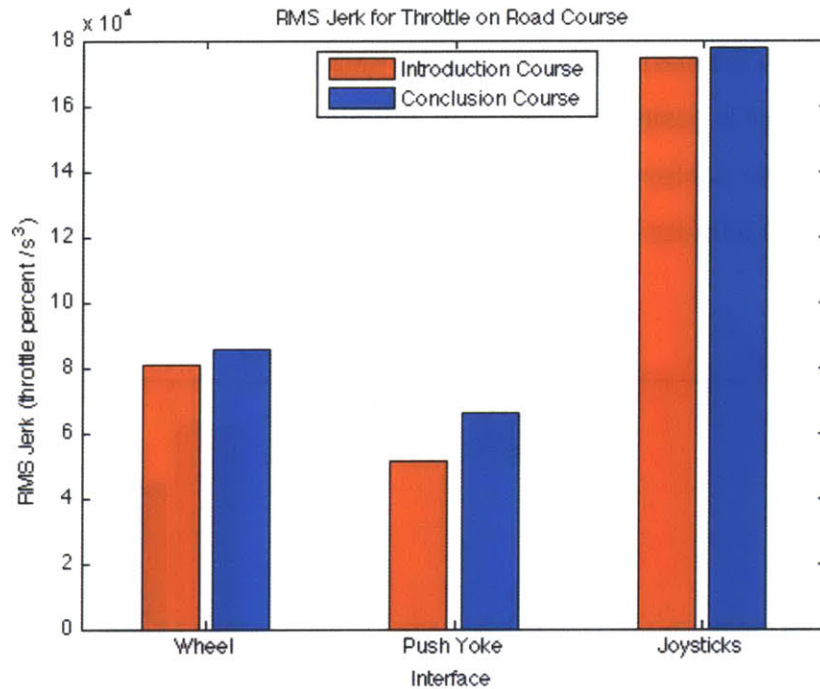
For steering, there is a dramatic difference in the RMS jerk among interfaces (Figure 4-1), showing that the wheel is easiest to steer with, followed by the yoke, then the joysticks. For all interfaces, the driver achieves some level of familiarity with the steering interface during the tests and has lower RMS jerk during the concluding road course.



**Figure 4-1 - Steering jerk for road courses (initial tests)**

The joysticks have a much greater RMS jerk for throttle than either the wheel or the yoke (Figure 4-2), and the yoke has slightly lower RMS jerk than the wheel. The yoke has a much higher range of motion than the throttle pedal does with the wheel, which is one reason

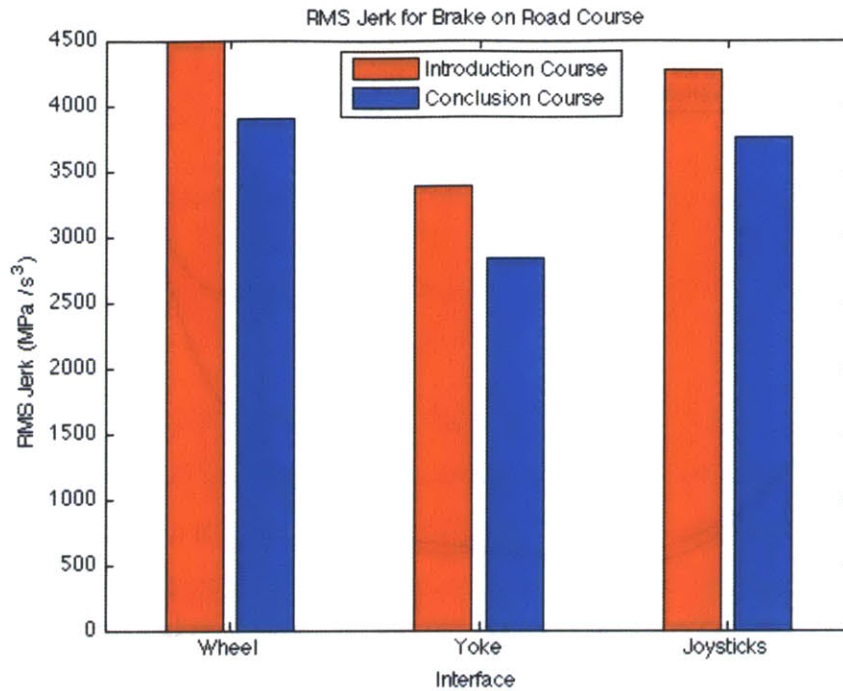
why it is easier for the driver to operate it smoothly. The joysticks have a much higher RMS jerk than the other two interfaces, and have a similar range of motion to the wheel's throttle pedal. Thus, to achieve smoother throttle control, the throttle's range of motion can be increased or the throttle can be decoupled in its physical movement from other controls so it is controlled by a dedicated part of the driver's body.



**Figure 4-2 - Throttle jerk for road courses (initial tests)**

The RMS jerk for braking (Figure 4-3) shows that the large range of motion the yoke provides does help with braking smoothness. The wheel and joysticks are very similar, though, which could be due to the specific design of the wheel's brake pedal. As with other components, the brake control can be made easier for the driver to use by increasing its range of motion or dedicating a body motion to it.

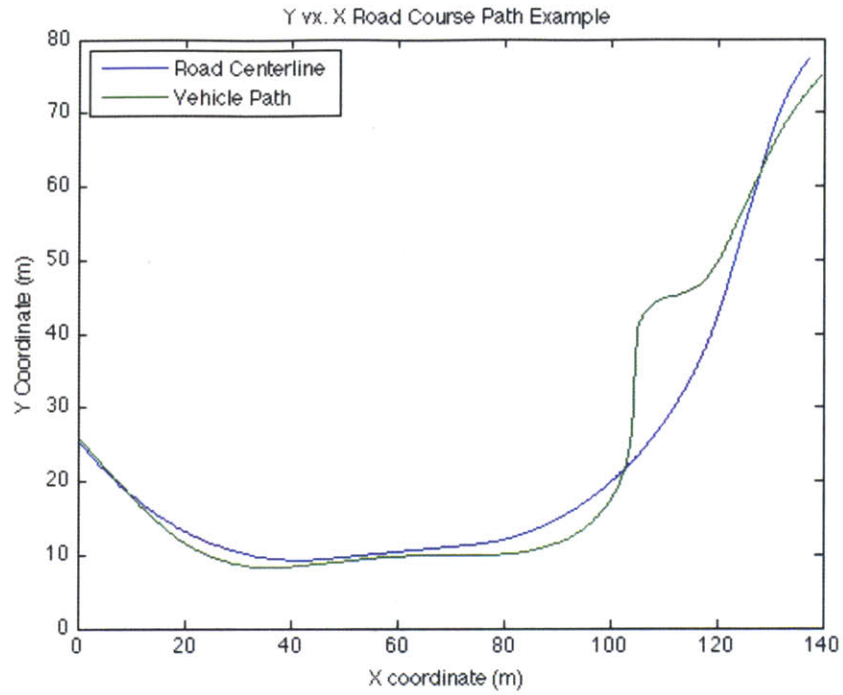




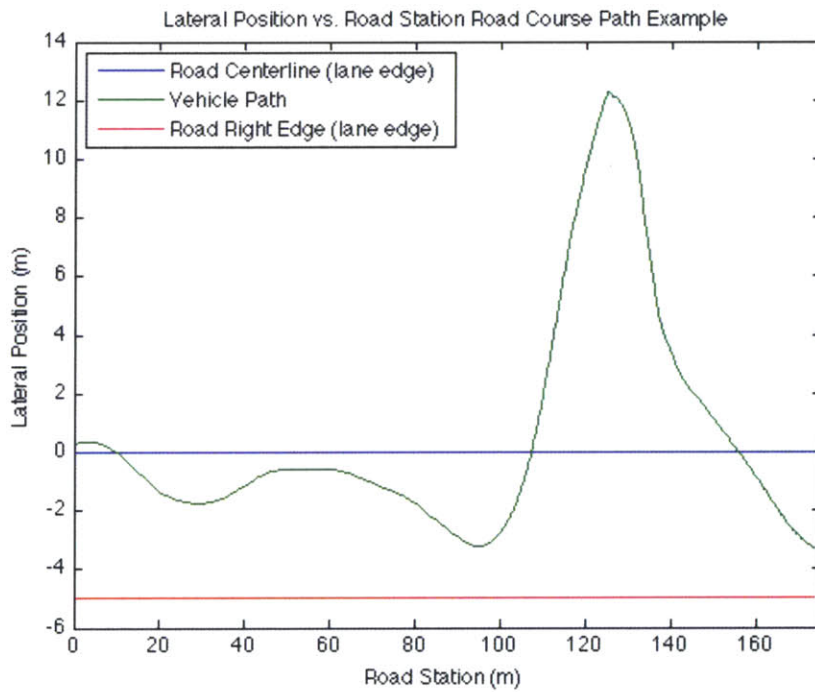
**Figure 4-3 - Braking jerk for road courses (initial tests)**

#### 4.1.2 Lane Following

Since the driver is instructed to stay in the right lane during the road course, the RMS error in lateral displacement on the road can be used to show how well the driver followed the lane. Figure 4-4 shows an example of the X/Y path followed by the vehicle during a particular test and the corresponding lateral displacement versus road station (distance along the track).



**Figure 4-4 - Example road course X/Y path**



**Figure 4-5 - Example road course lateral displacement path**

Since it is not specified that the driver should follow the very center of the right lane, the driver will naturally drift within the bounds of the lane under normal driving conditions. Therefore, only lateral error where a wheel leaves the boundaries of the lane is considered; if all tires are within the lane the error is considered to be zero regardless of the vehicle's specific position within the lane. The road course lane following error is shown in Figure 4-6.

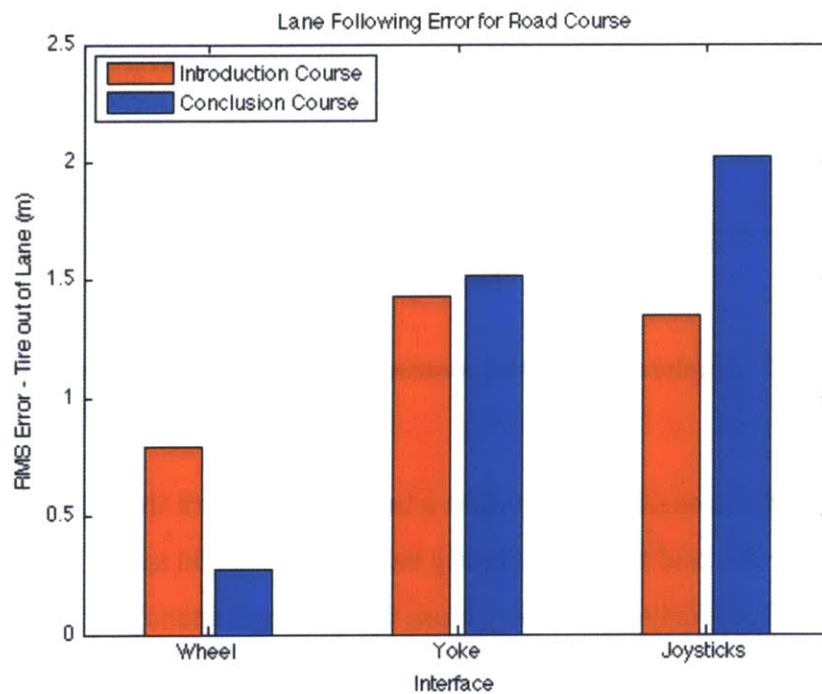
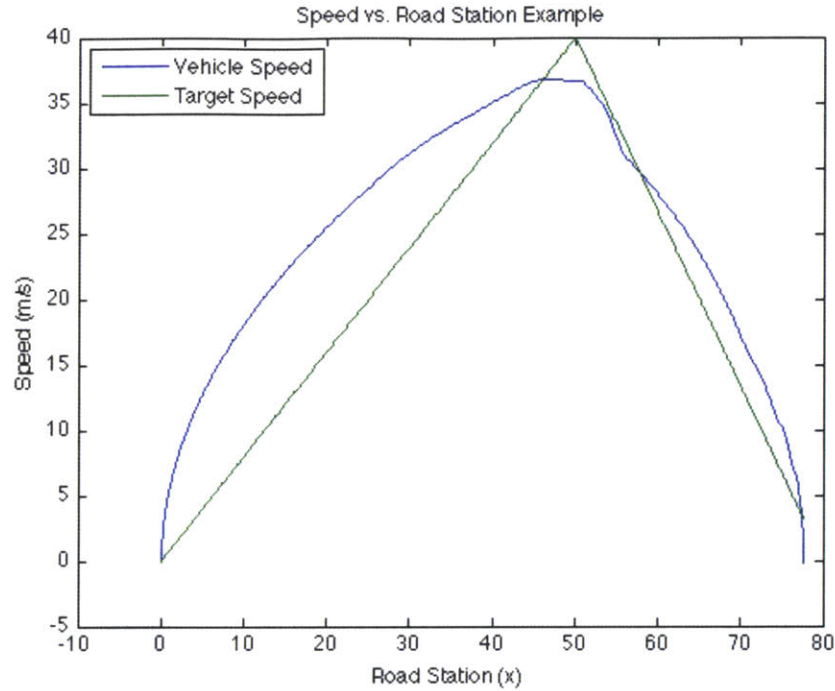


Figure 4-6 - Road Course lane following error (initial tests)

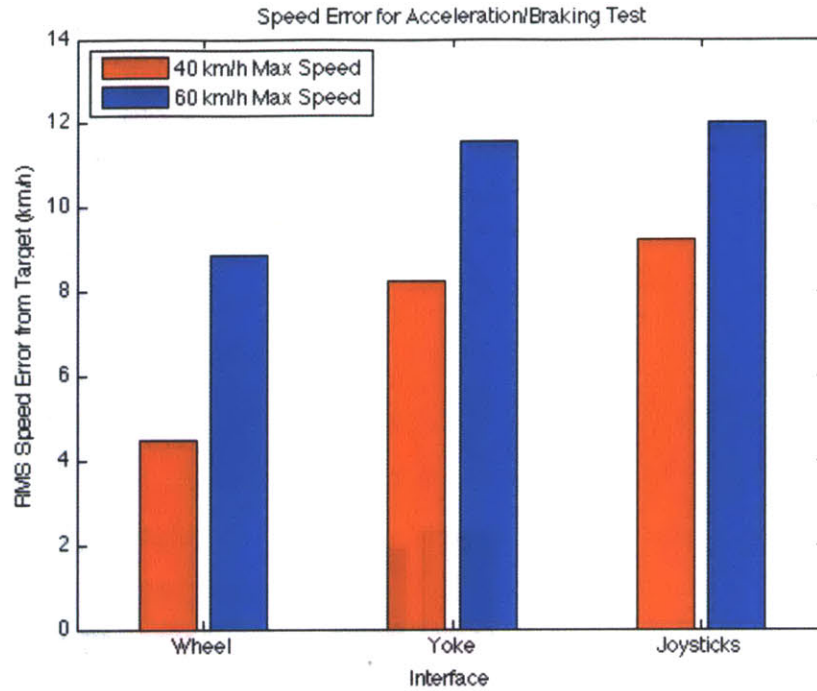
#### 4.2 Acceleration/Braking Course

The acceleration/braking tests are meant to isolate control of the throttle and brake to see how easy it is for the driver to steadily increase from stop to a target speed in a specific distance then slow down steadily to stop at a specific distance. Ideally, the driver would be able to achieve fully linear speed both speeding up and slowing down, so we can compare the error between target and vehicle speeds. Figure 4-7 shows an example from one test.



**Figure 4-7 - Acceleration/Braking course single-run speed error example**

Figure 4-8 shows that it is easiest to maintain a target speed with the wheel’s conventional pedals for throttle/brake, and that it is slightly easier to maintain speed with the yoke than with the joysticks. All test drivers are very close to the target speed just before braking, so the consistently larger error for the fast acceleration/braking tests more strongly reflects the inability to stop smoothly than accelerate smoothly.



**Figure 4-8 - Acceleration/Braking test speed error (initial tests)**

### 4.3 Slalom Course

The slalom course gives the driver an opportunity to primarily use steering while keeping a constant speed. As with the road course, interface usability can be measured by how smoothly the driver operates it. Figure 4-9 shows that the wheel is the easiest to use, followed by the yoke, then the joysticks.

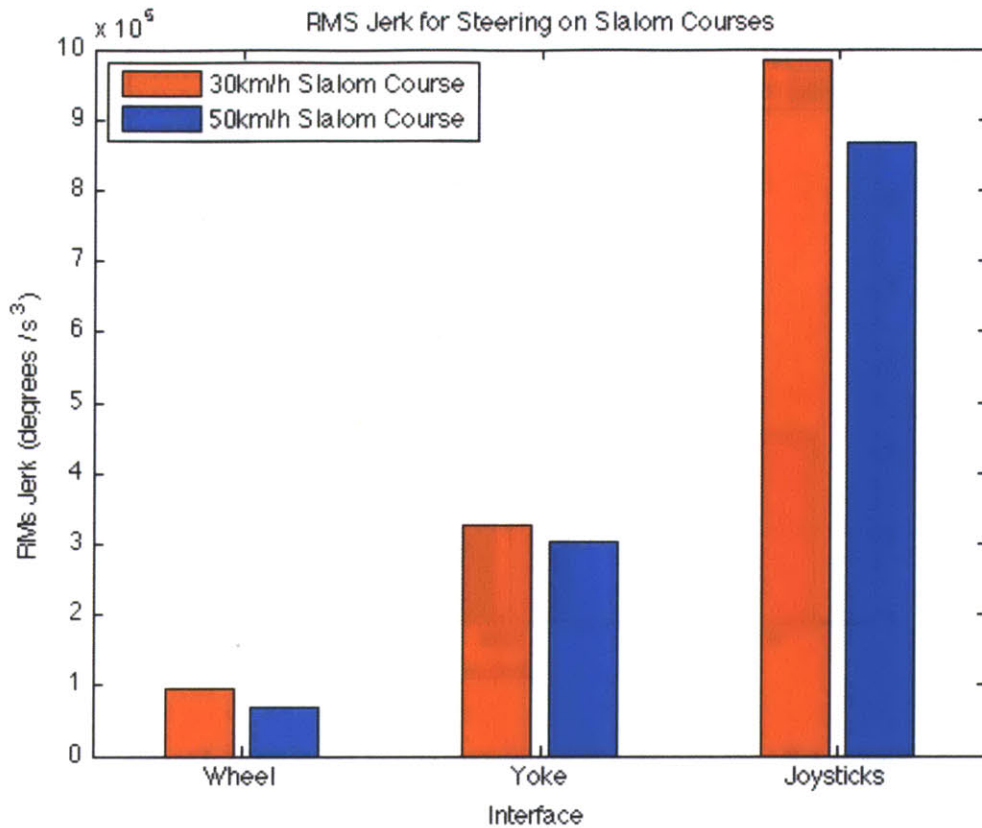
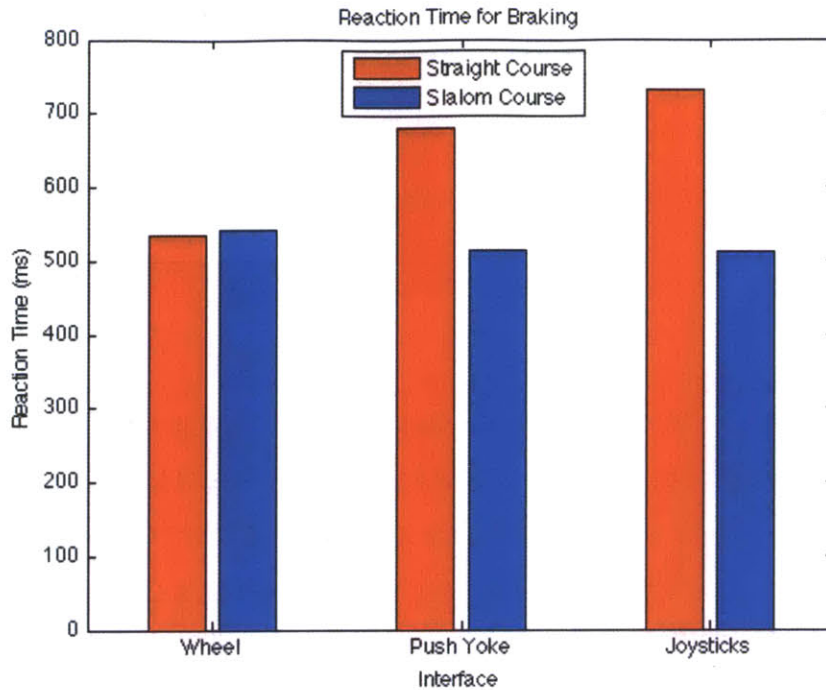


Figure 4-9 - Slalom course steering jerk (initial tests)

#### 4.4 Sudden Stop Courses

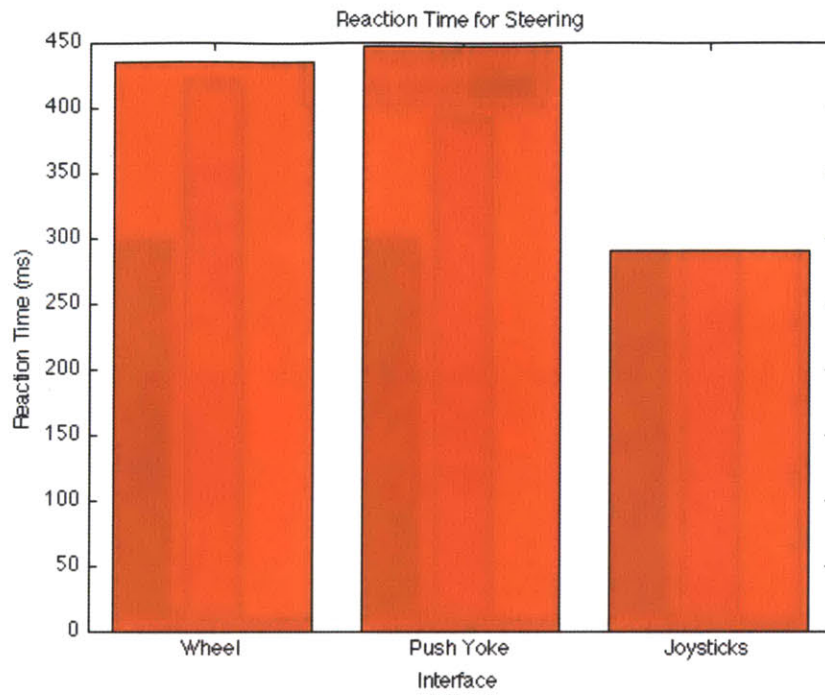
There is some difference for braking time among the interfaces on the straight sudden stop course (Figure 4-10). The familiar interface of the steering wheel provides the fastest reaction time since it is familiar to the drivers, while the other two interfaces have similarly slower reaction times. For the push yoke and joysticks, though, the reaction time improves to match the wheel's reaction time on the slalom sudden stop course, showing familiarity with the braking interface can be quickly achieved with only a small amount of training.



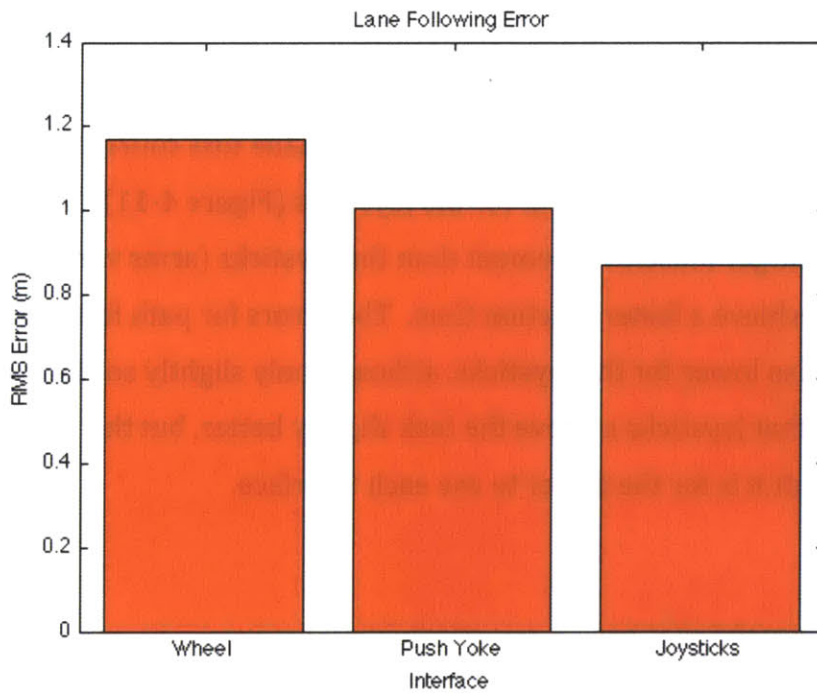
**Figure 4-10 - Braking reaction time on sudden stop courses (initial tests)**

#### **4.5 Lane Toss Course**

Reaction times for steering into the correct lane on the lane toss course were similar for the wheel and push yoke, but slightly lower for the joysticks (Figure 4-11). The steering wheel and yoke both use larger muscle movement than the joysticks (arms versus wrist), which help the joysticks achieve a faster reaction time. The errors for path following while changing lanes is also lower for the joysticks, although only slightly so (Figure 4-12). These metrics show that that joysticks achieve the task slightly better, but this does not take into account how difficult it is for the driver to use each interface.



**Figure 4-11 - Steering reaction time on the lane toss course (initial tests)**



**Figure 4-12 - Lane following error for lane toss course (initial tests)**



## **4.6 Qualitative Observations**

After the tests, the driver is asked to respond to a questionnaire that gathers the driver's opinion on each interface and asks for suggestions on improvement. The driver responses and my thoughts from observing drivers during the testing are grouped below by category.

### **4.6.1 Joystick Force Feedback**

With these gaming joysticks, the force feedback mechanism is not accurate enough to reliably keep the joysticks synced. They are kept in sync using a control loop developed in software, and tend to strongly oscillate unless the feedback is significantly dampened. This is likely due to a combination of slop in the joystick position input and the force feedback output. Because of this, a second joystick will not travel all the way to its extreme when the first joystick is pushed to the corresponding extreme. The user can also push the joysticks in opposite directions with little effort. Both of these things are sources of confusion for the user.

### **4.6.2 Steering Sensitivity**

For all interfaces, the steering sensitivity is a major factor for usability. For these tests, all interfaces are configured with a linear relationship between the deflection of the interface and steering wheel angle reported to the simulation. Users find that when they are driving faster, they have a harder time driving the vehicle with the joysticks and yoke because the interface's sensitivity is too high and they end up overcompensating. Mathematically, the overall "jerk" (the third derivative of position) for steering is greatest with the joysticks, followed by the yoke, then the steering wheel. One possibility to fix this is to change to the steering gain to be nonlinear. The steering wheel allows for a large range of linear motion because it uses multiple full rotations. In the CityCar, this is un-ideal because of physical limitations within the cockpit. Also, for a design where force-feedback is not feasible, allowing multiple full turns would present a problem for a spring return mechanism.

For a yoke with a smaller range of motion than a steering wheel, the driver would ideally be allowed to use close to the full range of motion during average driving conditions and only use the last small bit of the interface range for maneuvers that require turning the wheels to their furthest extent. The exact tuning of this nonlinear curve will be the subject of further study.

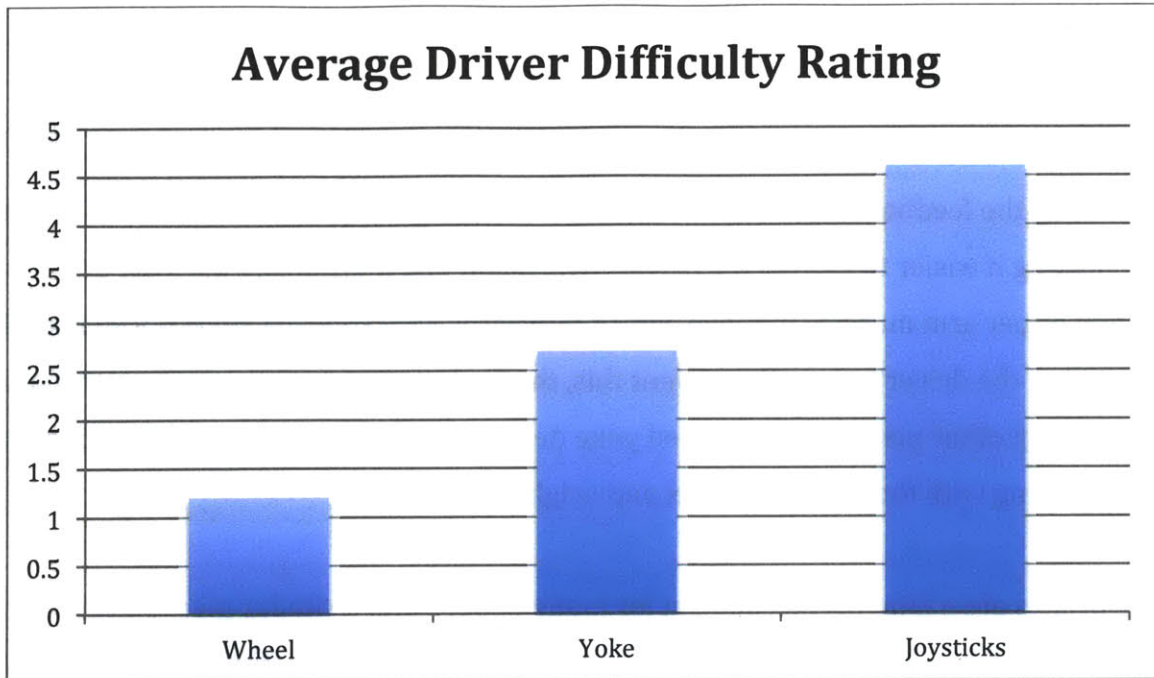
#### **4.6.3 Braking/Throttle**

For both the joysticks and the yoke, users find that the braking and throttle controls are too connected to the movement for steering. This commonly causes users to lose good steering control when required to change brake or throttle position while steering. This becomes particularly noticeable when the driver approaches a curve too fast and be required to steer while braking. This is more of a problem with the joysticks than the yoke because the joysticks have a smaller range of motion in both dimensions.

For the yoke to be a viable interface, the steering, throttle, and braking motions must be decoupled or they must be intuitive to perform at once. For braking, the current recommendation is a squeeze brake similar to bicycle brakes. The brake will take electronic precedence over the throttle, so brake and throttle are decoupled, and braking should be easier to perform while turning.

#### **4.6.4 Driver Difficulty Rating**

At the conclusion of the tests, the driver is asked to rate the perceived difficulty of each interface on a scale of 1 to 5 where 1 is the easiest and 5 is the most difficult. As Figure 4-13 shows, the relative ease of use as reported by drivers places the wheel as the easiest to use, the joysticks as the hardest, and the yoke between the other two interfaces.



**Figure 4-13 - Difficulty rating from drivers (initial tests)**

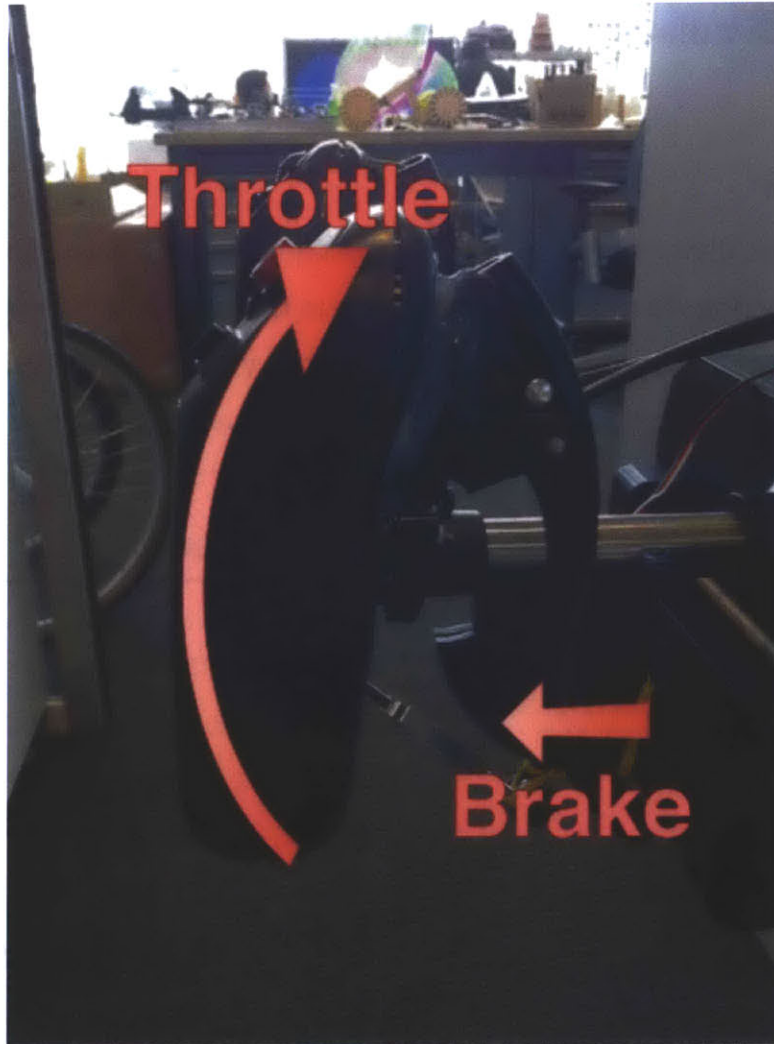
#### **4.7 Testing Conclusions**

Among these three driving interfaces, drivers find the familiar steering wheel the most easy to use. Because the steering wheel is an interface that drivers have significant experience with, and the other interfaces are new to the driver, it cannot be concluded that the steering wheel will always be the ideal driving interface. For the purposes of this study, it does provide a useful reference point for the other interfaces. The dual-joysticks are difficult to use, since they have a small range of motion and by design must allow different actions to interfere with one another. It is possible that the dual-joystick strategy can be an effective driving interface with substantial hardware and software revisions, but for this study the joystick is not used in the follow-up round of testing. The yoke did not perform as well as the steering wheel, but did perform better than the joysticks, and has potential to approach the usability of a steering wheel with design modifications.

## 5 Interface Revisions

The yoke is the interface that drivers found the most easy to use aside from the steering wheel. Using the feedback from the initial round of testing, the yoke is modified with the goal of making it easier to use for the driver. The push/pull mechanism uses the driver's lower and upper arm muscles to move, which interferes with steering since it also uses the same parts of the driver's arm. To prevent this, the braking and throttle mechanisms must be actuated by other means. This revised yoke design can then be compared in a follow-up round of testing with the steering wheel and original push yoke.

Bicycle brakes are a familiar mechanism for many people, and a similar mechanism can be integrated into the yoke behind the vertical handgrips (Figure 5-1). With the brakes in this position, the driver activates the brakes by squeezing the brakes between the fingers and palms. This does not interfere with steering, and having a brake on each side allows the driver to be able to safely brake with either hand in case only one hand is on the yoke when a sudden need to stop arises. The squeeze brakes can also be an intuitive response to a panic situation, as the driver is likely to react to an unexpected situation by gripping the yoke strongly.



**Figure 5-1 - Revised tilt yoke interface**

For throttle, a tilt mechanism is installed to allow the entire yoke to tilt forward on axis near the bottom of the yoke. This uses the driver's wrists to activate the throttle, and not interfere with either the brake or throttle motions. While it does not provide as great a range of motion as the original push yoke, the tilt mechanism will allow for the driver's hands to rest on the yoke, applying down and forward force to keep the throttle in a constant position with little effort from the driver.

# 6 Follow-up Simulator Testing Results

## 6.1 Road Course

On the road courses, drivers in the follow-up tests achieve similar smoothness ratings for steering on the steering wheel and push/pull yoke as the drivers in the initial tests (Figure 6-1). The tilt yoke is an improvement on the push/pull yoke for steering, indicating that a power function steering gain performs generally better than a linear gain.

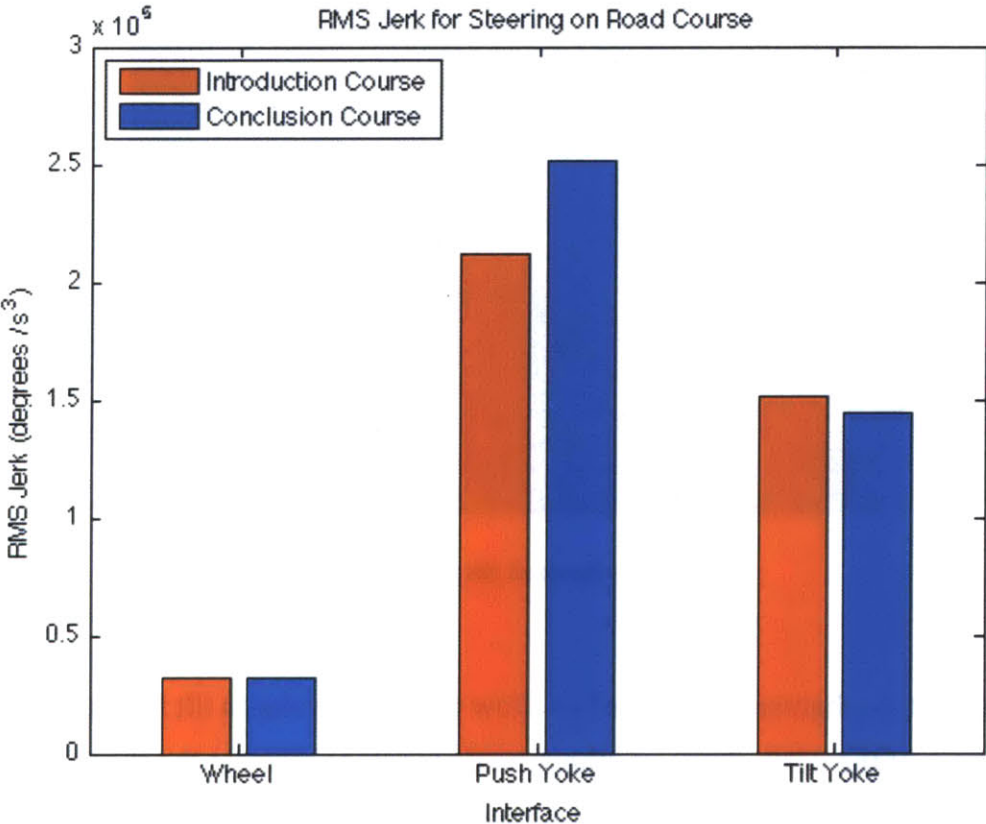


Figure 6-1 - Road course steering jerk (follow-up tests)

The tilt yoke performs slightly less well than the push/pull yoke for throttle (Figure 6-2). Even though the push/pull yoke steering interferes with throttle because they use similar body motions, the large range of motion of the push/pull yoke's throttle does help

minimize small variation in the throttle. With the tilt throttle, the driver will cause small movements in the throttle control with steering unless there is more physical damping.

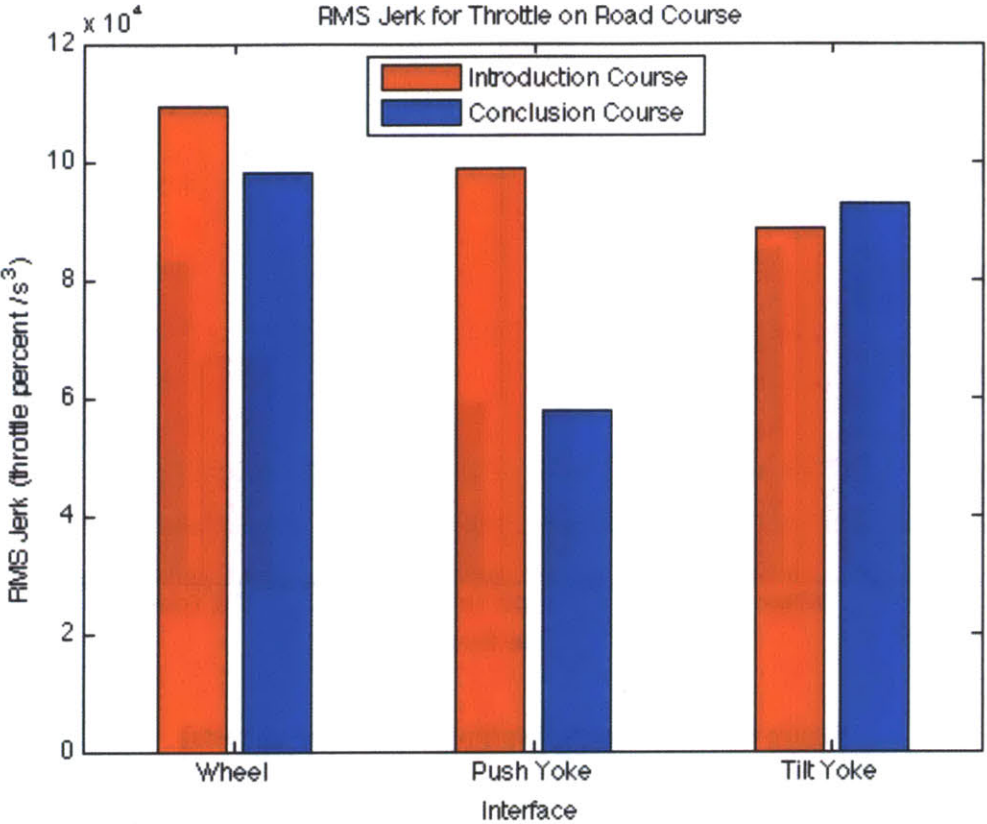
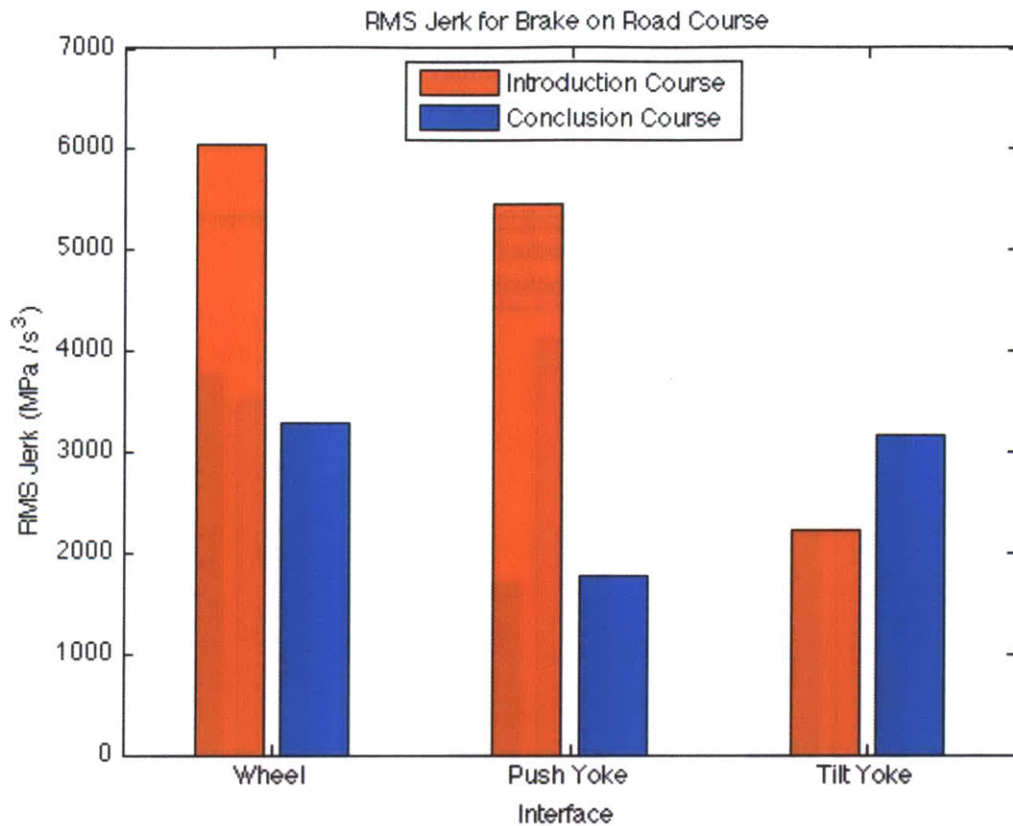


Figure 6-2 - Road course throttle jerk (follow-up tests)

For braking, the tilt yoke does perform slightly better than the other two interfaces (Figure 6-3). The tilt yoke, however, is the only interface where the braking jerk does not improve between the introduction and concluding road courses.



**Figure 6-3 - Road course braking jerk (follow-up tests)**

The push/pull yoke performs better than the tilt yoke in the follow-up tests for lane following (Figure 6-4). For the road course overall, this shows that the tilt yoke did not provide a general improvement in driving performance.



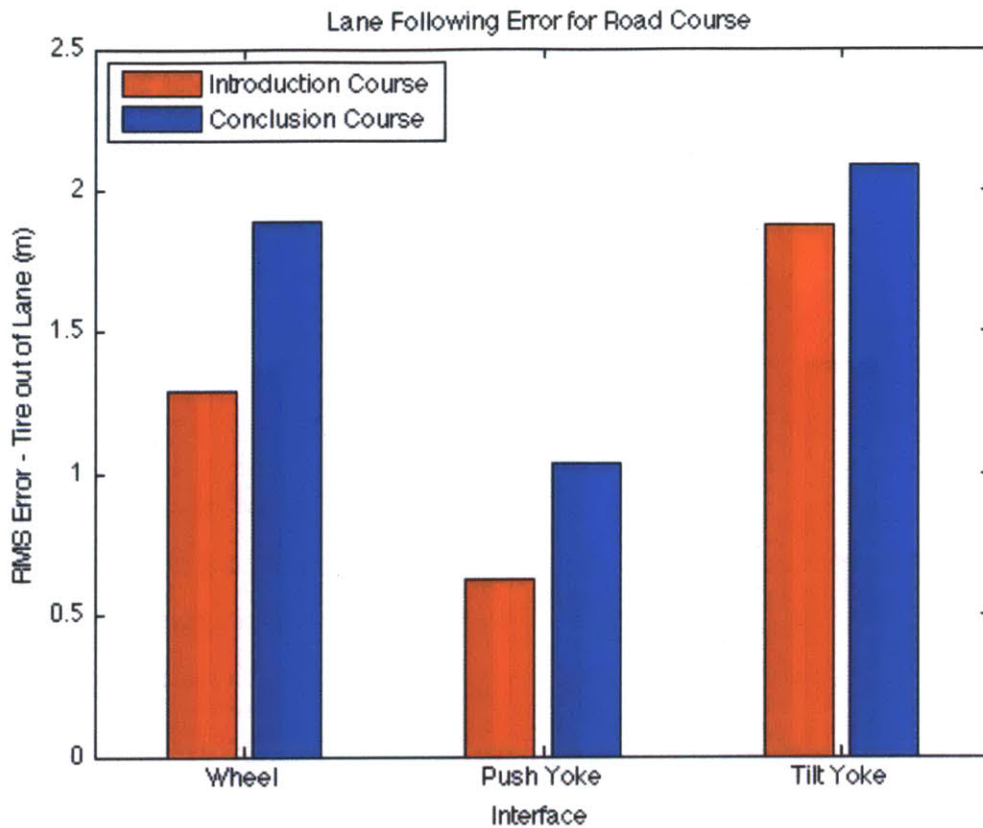


Figure 6-4 - Road course lane following error (follow-up tests)

## 6.2 Acceleration/Braking Course

The speed error for the acceleration/braking course shows that all interfaces performed approximately the same in this test (Figure 6-5). Since this test only uses the throttle and braking controls alone without steering, the primary design concern for a suitable brake control is allowing it to operate easily while the driver is steering.

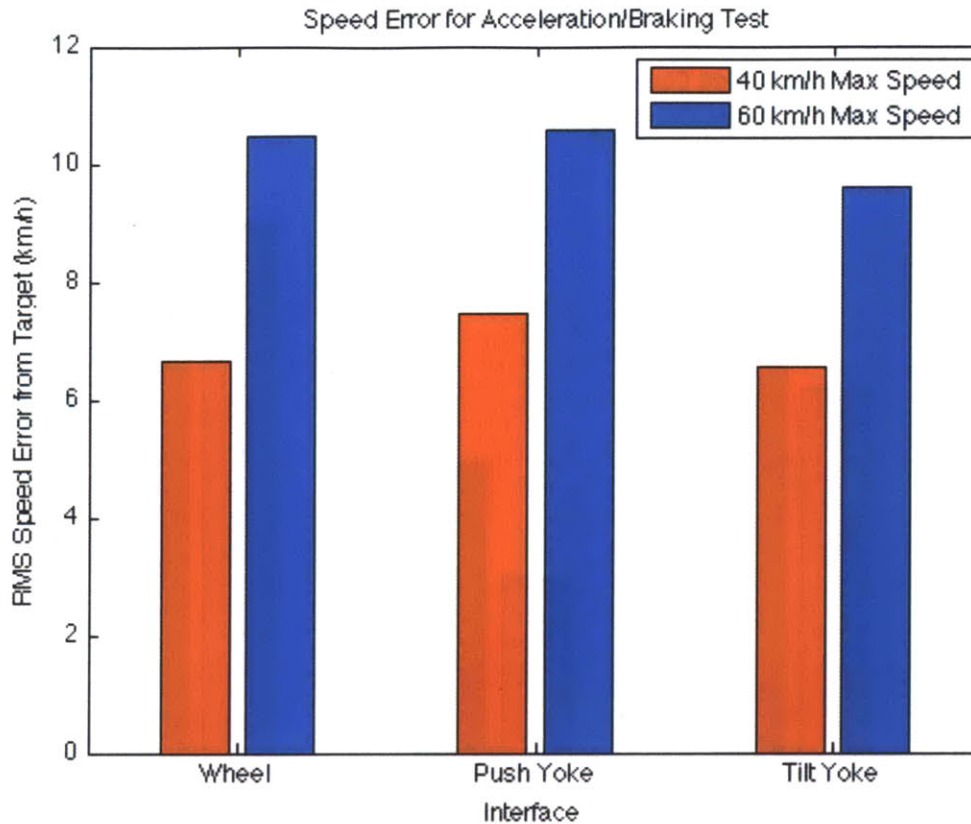


Figure 6-5 – Speed error for acceleration/braking (follow-up tests)

### 6.3 Slalom Course

Both yoke designs do not perform as well as the steering wheel on the slalom courses (Figure 6-6). The tilt yoke, however, does show a small performance gain over the push/pull yoke, again showing that the power function steering gain helps improve steering smoothness.

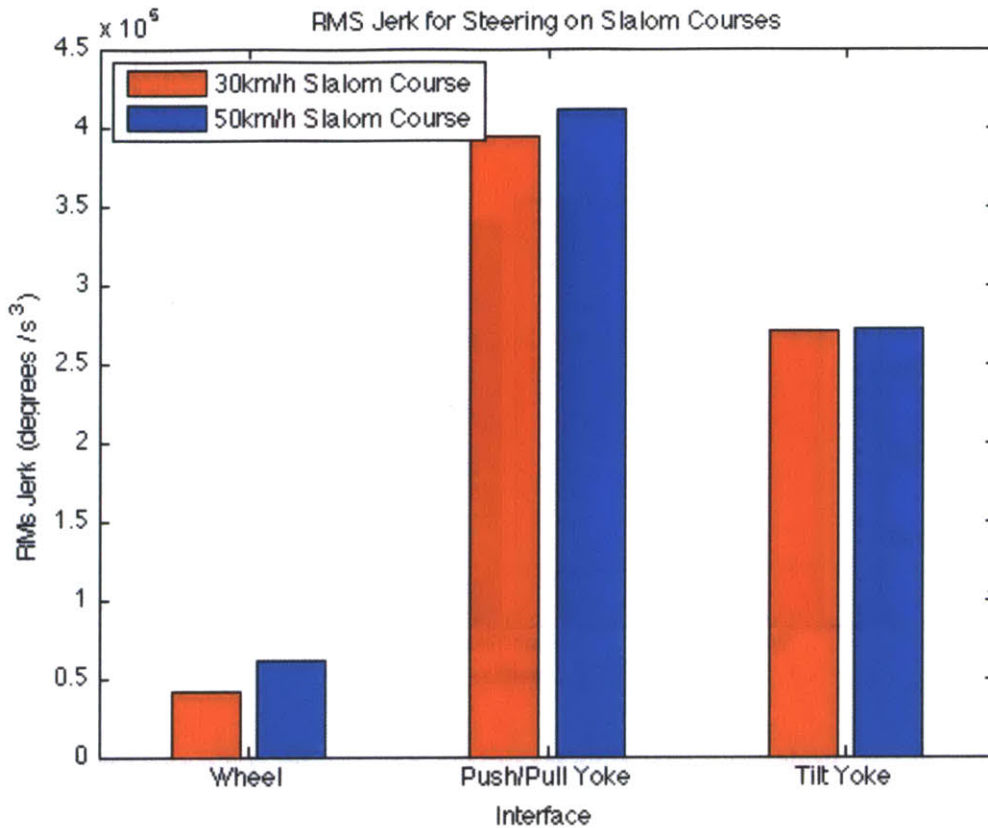
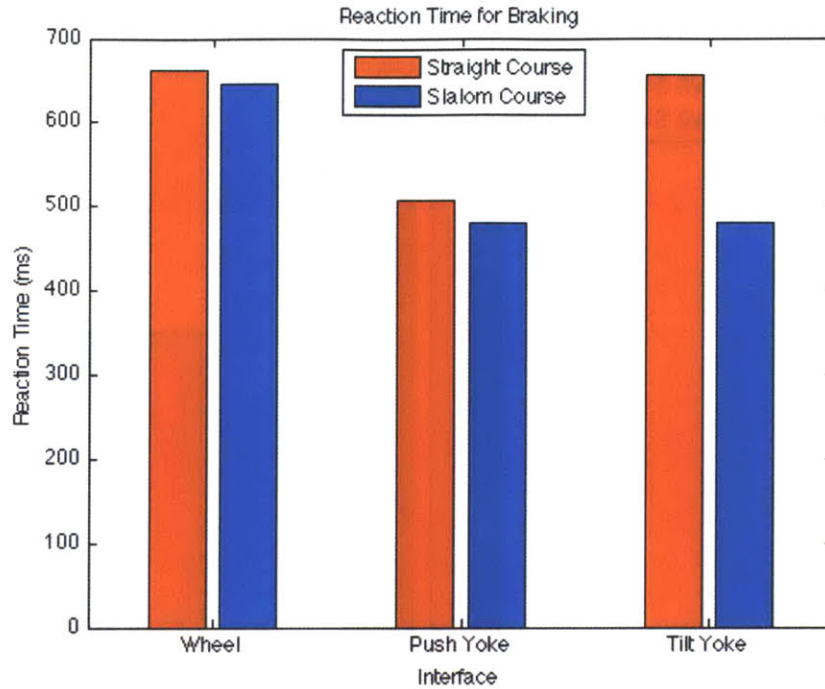


Figure 6-6 - Slalom course steering jerk (follow-up tests)

#### 6.4 Sudden Stop Courses

Reaction times for braking are quicker for both yokes than the steering wheel (Figure 6-7), although the tilt yoke only achieves a better reaction time on the slalom sudden stop. This shows for sudden braking, both yokes have the potential for achieving better reaction times than a brake pedal. Hand-controlled braking can be a viable alternative to foot-controlled braking.



**Figure 6-7 - Braking reaction time for sudden stop courses (follow-up tests)**

### 6.5 Lane Toss Course

Reaction times for steering are similar among all three interfaces for the lane toss course (Figure 6-8). Lane following error among the three interfaces is also similar (Figure 6-9). While this does not show a clear improvement with any interface, it shows that a yoke-like interface can achieve similar performance in a lane-change maneuver to a steering wheel.

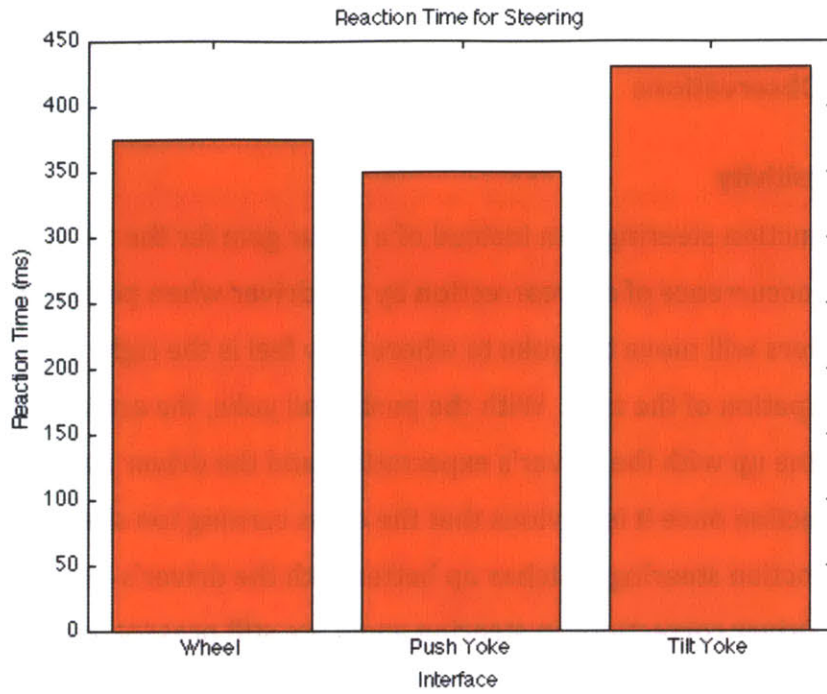


Figure 6-8 - Steering reaction times for lane toss course (follow-up tests)

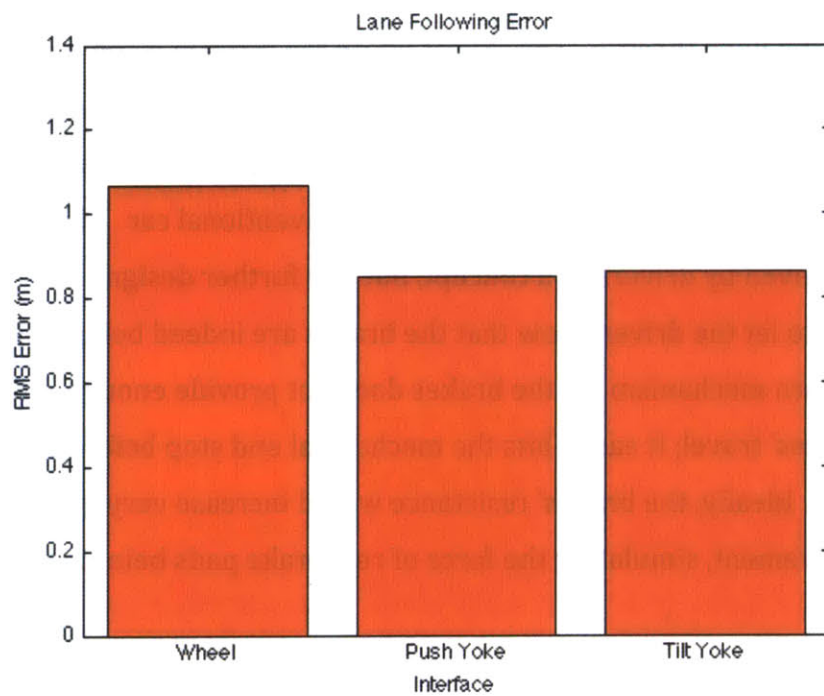


Figure 6-9 - Lane following error for lane toss course (follow-up tests)

## **6.6 Qualitative Observations**

### **6.6.1 Steering Sensitivity**

Using the power function steering gain instead of a linear gain for the tilt yoke appears to greatly reduce the occurrence of overcorrection by the driver when performing a turn.

With the yoke, drivers will move the yoke to where they feel is the right position as they go into a turn in anticipation of the turn. With the push/pull yoke, the actual required steering position does not line up with the driver's expectation, and the driver must quickly correct in the opposite direction once it is obvious that the car is turning too sharply. With the tilt yoke, the power function steering matches up better with the driver's expectations when going into a turn. Driver corrections in steering angle are still present, but greatly reduced.

### **6.6.2 Braking/Throttle**

Quantitatively, the throttle and brake controls do not show significant improvement in the tilt yoke design. Drivers, however, note that the concept of a tilt throttle is more comfortable than the push throttle. The axis of tilt on the throttle is too high and far forward with respect to the yoke. Moving this axis down and back would allow the driver to more easily use the weight of his hands to maintain a fixed throttle position, much like the driver resting a foot lightly on the gas pedal in a conventional car. The brakes are also generally well-received by drivers as a concept, but any further designs need stronger physical feedback to let the driver know that the brakes are indeed being fully applied. Using a spring return mechanism for the brakes does not provide enough resistance near the end of the brakes' travel; it easily hits the mechanical end stop before the spring force becomes too large. Ideally, the brakes' resistance would increase very quickly near the end of the range of movement, simulating the force of real brake pads being applied.

### 6.6.3 Driver Difficulty Rating

As shown in Figure 6-10, drivers find the wheel the most easy to use, while the push/pull yoke is the most difficult to use. The tilt yoke achieves a rating almost halfway between the wheel and the push/pull yoke.

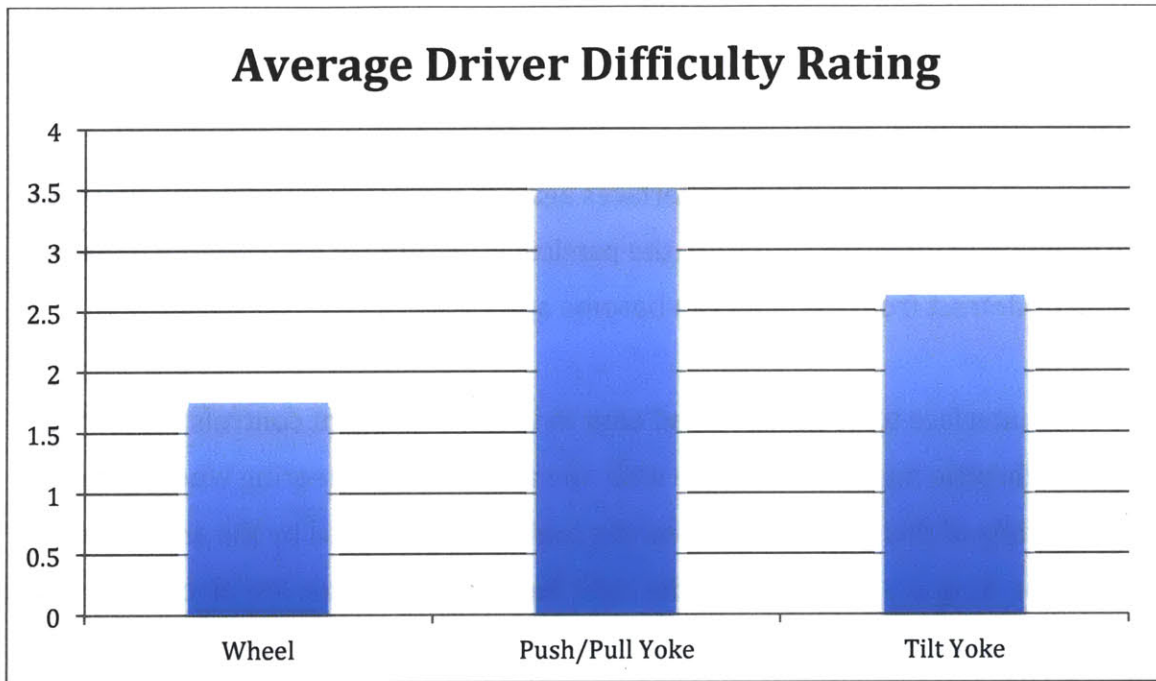


Figure 6-10 - Difficulty rating from drivers (follow-up tests)

### 6.7 Testing Conclusions

Overall, drivers do prefer the tilt yoke to the push yoke, despite some of the metrics above that indicate that the tilt yoke did not perform as well. The power function steering gain effectively provides access to a large output range of motion to the wheels with only a small range of motion from the yoke's steering input. The tilt mechanism does not provide a significant performance gain in this particular version, but it

## 7 Conclusions

While this study does not find an alternative driving interface that could be directly suitable as a replacement for the conventional steering wheel, examining these alternative interfaces and their shortcomings can help influence the design of new interfaces.

### 7.1 Design Principles

By directly comparing these driving interfaces against one another and evaluating their relative usability in different scenarios, the particular features of each interface that contribute or detract from usability can become apparent.

For a driving interface to be intuitive and easy to use, the different controls of steering, braking, and throttle must not interfere with one another. The steering wheel is most extreme example of this concept; the steering control is controlled by the arms whereas throttle and braking are controlled by the right foot, and the pedals are placed in a way to encourage only using the right foot so that both cannot be activated at once. Driving controls that do not use the driver's legs are possible, though. Any driving interfaces similar to the ones tested can use a few basic motions from the driver as control, and must not allow any one of these motions to affect multiple driving controls. The driver's arms can translate the hands in any direction, the driver's wrists can also rotate to supply input, and the driver's fingers and palms can be used.

When mapping a large range of motion on the output of the car to a control input with a small range of motion, nonlinear gain can achieve the desired sensitivity in different parts of the control. For steering, the center of the control must not be too sensitive, or the driver will have difficulty maintaining a straight path and making small course corrections at higher speeds. The gain can be increased near the extremes of the steering range as well, since these steering angles are only used during low speed maneuvers. Braking and throttle must also provide enough tactile response to convince the driver that the control is being effective. With drive-by-wire, there is no inherent feedback to the driver from the



underlying control systems, so the artificial tactile response should mimic the behavior of the mechanical counterpart to make drivers comfortable who are familiar with conventional controls.

## **7.2 CityCar Interface Direction**

For the CityCar specifically, this study shows that the best interface direction to use is the yoke interface. The steering motion is similar to a conventional steering wheel, which will allow drivers who use CityCars in a shared-use scenario to quickly become familiar with the new driving interface. The bicycle-like brakes are another mechanism that is familiar to most drivers. These features will allow the CityCar to be as familiar as possible to new users while still achieving the goals of keeping the front of the cockpit free of pedals and having an interface that can be moved out of the way easily.

## **8 Further Study**

Even though this study provides a basic understanding of the benefits and drawbacks to alternative driving interfaces, there are certainly opportunities for further study. Even though concept cars are increasingly being designed with alternative driving interfaces, there will be some time before any of these solutions are seen on the commercial market, giving an opportunity to refine these interfaces.

### **8.1 More Robust Mechanical Interfaces**

In this study, the alternative driving interfaces were not industrial-quality mechanisms. Because of this, there are times when there is a small amount of slack in the steering connection, which can make the yoke feel loose when it is at the center position. Very fine movements are also sometimes difficult to perform, which can cause the driver to overcorrect. This cannot be corrected with different types of movements (tilt versus push, for example). To achieve effective control with fine movements, the alternative interfaces

to be tested must be custom-manufactured with higher precision than available for the interface mockups in this study. With more precisely manufactured interfaces, there can be more accurate comparisons of subtle design differences between interfaces.

## **8.2 Direct Comparison of Force-Feedback**

The steering wheel and dual-joysticks in this study used force-feedback to attempt to give the driver a sense of control over the vehicle, but directly comparing the same interface with and without force feedback was not a goal of this study. In future explorations, the same interface could be manufactured with passive mechanical feedback and with computer-controlled force-feedback, and these two could be directly tested against one another. In particular, isolating what types of controls benefit from force-feedback would allow manufacturers to leave out unnecessary complexity. For example, force-feedback for steering might be far more important to the driving experience than force-feedback for braking. Since physical feedback is the main thing that drive-by-wire removes from a vehicles control interface, it is important to determine exactly how much of the feedback that drivers normally experience with physical controls is truly necessary to driving.

## 9 Works Cited

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