Title
Controls and Dynamic Analysis of Automotive Systems Using Electronic Model Scale Vehicles

Author
Sapong, Nathan O.

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CONTROLS AND DYNAMICS ANALYSIS OF AUTOMOTIVE SYSTEM USING ELECTRONIC MODEL SCALE VEHICLES

By

Nathan O. Sapong

A capstone project submitted for Graduation with University Honors

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APPROVED

Dr. Sundararajan Venkatadriagaram
Department of Mechanical Engineering

Dr. Richard Cardullo, Howard H Hays Jr. Chair
University Honors

ABSTRACT

Human-controlled vehicle operation on roadways and highways poses a significant risk to the transportation environment due to the human error. Thousands of people are killed or injured by vehicle accidents yearly, many of which could have been avoided with stronger safety measures and precautions. Autonomous controls and self-driving vehicles provide an alternative to improve safety in the transportation industry. Furthermore, it is imperative that the design and implementation of the vehicle system are in accordance with predictive scenarios and that proper prototyping, testing, and analysis are performed to ensure the safety autonomous systems in exists transportation environments. This project explores the feasibility of analyzing vehicle systems using scaled remote-controlled vehicles. Using MATLAB, dynamic and control analysis is performed to analyze scale model vehicle motion within a preset testing environment with environmental factors. Controls are implemented in simulation with intention to apply developed methods to a hardware testing environment. Studies, simulations, and tests will be evaluated using real-world testing parameters and vehicle performance data. Real-world data used for the simulation study included the dimensions a 1:16 remote control vehicle and stop-and-go traffic data of New York City from the United States Environmental Protection Agency (EPA). This project’s results demonstrate the importance of initial conditions, sensor sensitivity, and algorithm robustness in avoiding high-speed collisions and maintain a safe transportation environment.

ACKNOWLEDGEMENTS

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Introduction

Autonomous vehicle guidance, navigation, and control are a clear direction for the transportation industry for the development of automobile systems. Autonomous vehicle systems, or self-driving vehicle systems, are capable of moving safely depending on their environment with little to no input from manned driver or an external remote controller. In order for autonomous vehicle systems to properly navigate safely, it is imperative that the design and implementation of autonomous systems are capable of addressing predictable scenarios common to the road environment. However, the design and manufacturing of individual, full-scale autonomous vehicle prototype systems for comprehensive analysis are expensive and resource-intensive. Such testing is limited to the resources available to the analysis team and commonly consists of only a few key, ideal test scenarios. This creates a limitation for autonomous vehicle testing as full-body prototyping and testing can be arduous and costly.

This project proposes an alternative to full-scale, autonomous vehicle prototype for comprehensive analysis using autonomous electronic scale models and simulation environments. Using software and hardware, this project demonstrates the use of engineering analysis and simulation to provide findings on the navigation behavior of autonomous, scale-model vehicles. Simulation models in MATLAB were performed to develop a control algorithm capable of identifying, altering, and correcting the driving force needed to prevent vehicle collision. To incorporate real-world testing data for model verification, the simulation models were derived from an existing scale model, electric, RC vehicle with intention for future use in hardware testing. Travel data was based on low-speed, stop-and-go driving schedule from the United States Environmental Protection Agency to create a realistic, expected behavior model for the simulated, autonomous scale vehicles. The project created a car-following model so that a follower car safely and quickly follows a leader car at the appropriate distance by adjusting its speed to match the leader car.

Background

Travel by automobile is one of the most common, commercial methods of transportation along with air or sea travel. Most cars are two- or four-wheel drive vehicles used for travel on road conditions, such as freeways, highways, streets, and building complexes. Certain vehicle models capable off-road travel conditions in mud, dirt, and other natural environments; however these are not targeted by this research.

Manned automobile travel is a dangerous necessity in today's consumer culture. According to a 2008 study conducted by the Experian Automotive, the average U.S. household owns approximately 2.28 with the most common vehicle combination being a standard, mid-range vehicle and a large pickup truck [1]. Regardless of environment or location, it is evident that the average American household values access to or ownership of multiple vehicle and transportation options. Multiple vehicles per household allow multiple household members access to travel. In addition, each unique vehicle type per household addresses the limitations and needs of the individual household. This study, published in 2008, consisted of human-input or human-controlled vehicle transportation methods because autonomous vehicle navigation was still in development and was not yet capable of operating fully on American highway systems.. Due to human-error, environmental conditions, road conditions, debris, and other roadway irregularities, there is a considerable amount of risk involved when operating a standard automobile. In 2019, the National Highway Traffic Safety Administration (NHTSA) reported 36,096 people lost their lives in motor vehicle accidents [2]. Many of the accidents could have been completely avoided or mitigated by removing, controlling, or accounting for the sources of error.

Automation technologies provide a safer transportation alternative for automotive systems. Automated vehicles (AV), the alternative for human-driven vehicles, plan to address the growing concerns of road safety by allowing the human input error prevalent in current vehicle technologies. However, there exists different levels of automation between human-driven systems and fully automated systems which define the capabilities, applications, and uses of the overall system. The NHTSA has defined a five-level hierarchy to categorizing the degrees of autonomy present in vehicle systems [3]. Shown in Table 1, the continuum of vehicle autonomy is summarized. For example, existing technologies such as dynamic braking support and electronic stability are classified as function specific automation. Dynamic braking support and electronic stability are both considered Level 1 autonomous controls as each system addresses a specific function of the vehicle system.

Autonomy Level	Examples
Level 0 (No Automation)	• Fully manned vehicle system • No assistive or automatic systems
Level 1 (Function-Specific Automation)	• Specific, pre-defined vehicle functions activate at the vehicle's discretion • Common for built-in emergency systems

Level 2 (Combined-Function Automation)	• Vehicle and manned driver share authority over specific driving conditions • Combination of functional automation addresses vehicle subsystems rather than components
Level 3 (Limited Self-driving Automation)	• Vehicle is capable of navigation with occasional driver input • Specific to traffic and environmental conditions
Level 4 (Full Self-Driving Automation)	• All safety critical systems are operated and commanded by the vehicle • Driver is not needed for navigation or control during travel

Table 1. Examples of controls, systems, and components present in autonomous systems based on the NHTSA's five-level hierarchy for autonomous vehicles.

Autonomous vehicle systems can greatly reduce the number of risks, car accidents, and crashes that result in the death of thousands of people each year. Studies show that human error remains a major factor in approximately 90% of all car accidents and were avoidable or preventable [4]. Autonomous controls can address the case of human error by removing human-controlled input from the system. In order to achieve this, autonomous vehicles must be accurately tested and analyzed to ensure their navigation methods are capable of performing on existing road conditions. However, current road infrastructure is designed for manned input and unideal for testing newly designed autonomous systems. Similar to existing manned vehicle testing and prototyping, corporations must also perform complete comprehensive analysis of their proposed vehicle systems before implementing their technologies onto the road. Limitations of full-scale autonomous vehicle testing include the manufacturing and design costs of model prototyping [5]. Due to dependability on funds and resources, testing is limited to ideal road conditions for testing [5]. The results, therefore, are limited to the extensiveness of the prototype's testing environment. Without proper consideration of unideal terrain, such as uneven pavement, cracked or damaged road cement, scattered debris, and sudden stops, the future of autonomous vehicle navigation would unsafely operate on the current road infrastructure.

Methods

Autonomous vehicle prototyping and testing are essential procedures to ensure the safety of the transportation sector. This project demonstrates the use of remote control (RC) scale model vehicles as use for data collection and future conversion to autonomous systems. The navigation and control of the vehicle will be simulated in software and tested using analytical methods in a predefined test environment, allowing for customizability of vehicle models, navigation controls, environmental characteristics, among other factors.

Model Selection

The vehicle selected for scale model testing was based on a number of criteria: size, weight, speed, dimensions, mechanical properties, operation time, and vehicle layout. The size of the vehicle had to be relatively small compared to the actual dimensions of autonomous commercial vehicles. This was necessary to ensure the scale model aspect of the design, incorporate future hardware testing with multiple vehicle bodies in set test environments, and to assess the feasibility of the scale model research for autonomous vehicle simulation models. Weight remained an important factor for calculating the drive force produced from the electronic scale model. Dimensions and mechanical properties are used to determine the scale factor of the scale model, the geometric characteristics of the vehicle body for determining the width and length of the simulation model, and the material properties used for analytical calculations. In addition, resistance forces such as drag force and tire friction are dependent on geometric design and material composition of the model vehicle. In addition, the vehicle must resemble and behave similar to existing, commercial automobiles. Operation time is a critical aspect of the model as it is dependent on the system's battery life. A long, reliable battery is necessary to allow the vehicle to operate for extended periods of time. Moreover, the addition of external, electrical hardware components will require a power source. A favorable battery life would allow the model to become fully self-sufficient, powered from one main source. This can be resolved by adding an accompanying power source to vehicle, allowing for the external hardware the vehicle to be powered by two designated power sources. The final criteria, vehicle layout, refers to the internal makeup of the model. For future hardware simulation, a vehicle body with ease of accessibility to vital components, such as batteries and motors, along with areas for housing external electric hardware are preferable. Options for vehicle selection included purchasing of RC car models, development of unique prototypes, or a combination of both.

The vehicle selected for simulation was a MIEBELY RC Cars 1: 16 Scale All Terrain 4x4 Remote Control Car, shown in Figure 1. This vehicle is composed of four rubber tires attached to a spring supported plastic frame. The rubber tires are designed with small protrusions ideal for travel in various environmental conditions ranging from flat ground to off-road terrain. The vehicle chassis includes a brushed DC electric motor and a 500mAh 7.4 V lithium-ion battery. The scale model vehicle is capable of accelerating and decelerating from max speed to stoppage within seconds. The exterior of the chassis is protected by a thin plastic exterior car body. The car body is smooth, lightweight, easily replaceable, and prevents debris from compromising the internal system. Along with the car body, the rear spoiler of the care frame provides favorable aerodynamic principles to the vehicle body.

Figure 1. Internal view of the MIEBELY model RC car shows a removable car body, allowing for simple access to vital electric components.

Simulation Model

A test course for the scale model simulations was developed in the MATLAB interface. Figure 2 depicts the final result of the test course design. This course represents a single lane of standard road infrastructure with a dotted line representing the computed center distance between the lane boundaries, represented using solid black lines. Vehicle models begin the test course in the bottom left-hand corner aligned with the mid line. Testing was performed by moving the vehicles from the starting position using two vehicle models, represented by using different colors.

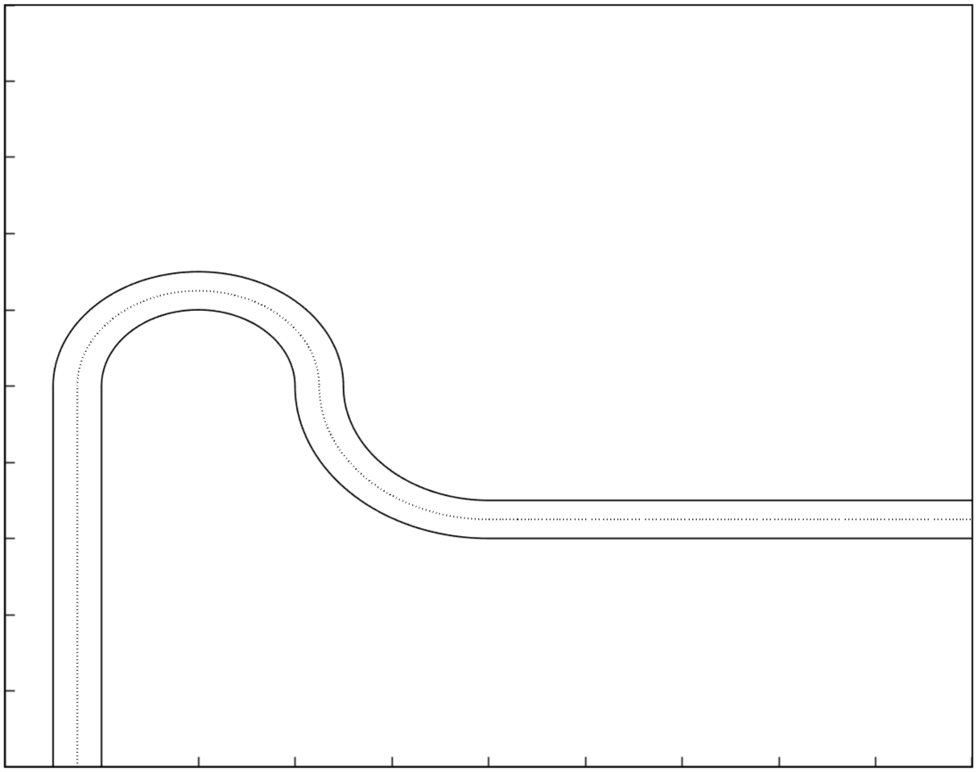

Figure 2. Simulation test environment developed in MATLAB.

There are two vehicle models present in the simulation environment and differentiated using colors. Vehicle 1, the red vehicle, and Vehicle 2, the blue vehicle, are both generated onto the MATLAB simulation environment using the polygon function with MATLAB. As per the MATLAB polygon function, the vertices of the vehicle body must be defined in a counter-clockwise or clockwise order to preserve the rectangular shape of the vehicle. Figure 3 displays the computational method used to define location of all vertices relative to the vehicle center. As dimensions of the vehicle are unchanged, the location of all four vertices can be computed knowing the location of the vehicle center and the current rotation of the vehicle model.

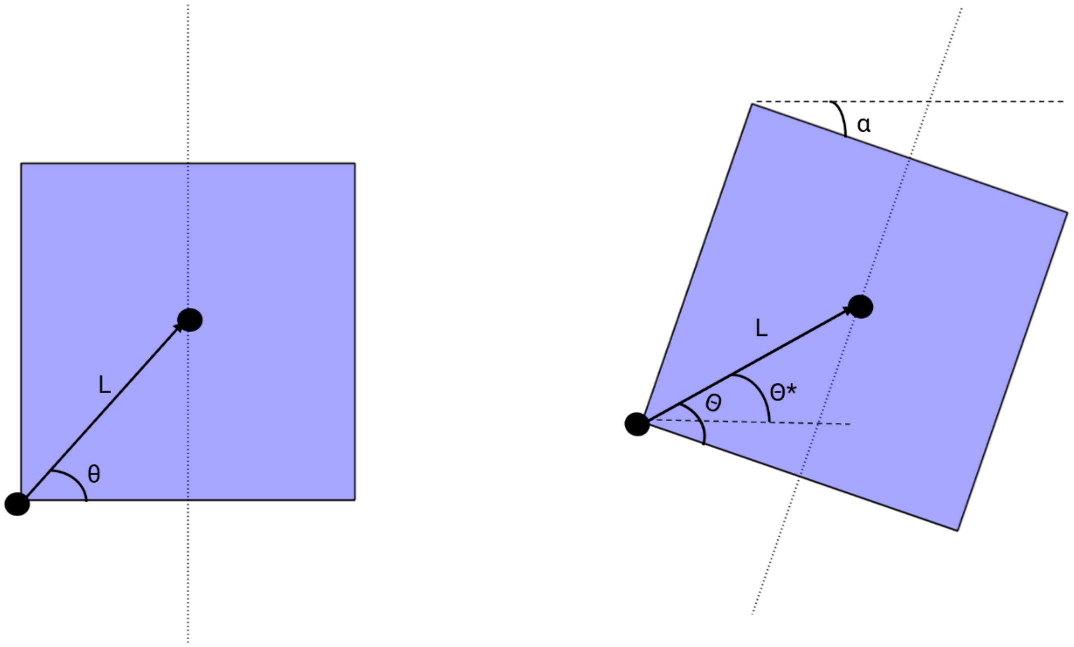

Figure 3. The vector approach for the boundary conditions of the simulated scale model vehicles depends on actively on the rotation of the vehicle and current location of the center.

As the vehicle dimensions are constant, both L, the distance from the vehicle center to the left-corner vertex, and θ, the angle between the vehicle center and left-corner vertex, are constant throughout the simulation model. This allows for the left-corner to be represented using a vector and all other remaining vertices to represent using the definition of the rectangular frame. However, all vertices rotate about the center point equally during turning events while also translating due the motion of the vehicle. Knowing the steering angle, defined as α, θ* can be represented using Equation 1.

$$\theta^{*} = \theta - \alpha \tag{1}$$

Both vehicle models are loaded into the system directly behind one another, sides parallel, as to resemble a common situation for road vehicles such as parking or remain still at a stoplight. Vehicle motion begins by moving down the road path, or upward in simulation as show in Figure 4. Both vehicle blocks are equipped with sensors to actively measure the distance between the rear bumper of the vehicle in front and the front bumper of the vehicle behind the starting vehicle. These sensors actively detect and communicate data to the vehicle blocks with little to no delay, as to resemble high-speed ultrasonic wave sensors commonly used in autonomous vehicle technologies. Motion in Vehicle 1 is computed accounting for the environmental characteristics a scale model vehicle would encounter during testing runs, namely aerodynamic drag force and friction force shown in Equation 2 and Equation 3, respectively. Due to the sleek exterior of the car body, the aerodynamic drag force is relatively small due to the cross-sectional (A_S) being relatively small and designed to mitigate incoming airflow. C_d is the drag coefficient and for simplicity is assumed to be 0.35. The density of air (ρ) is approximated at 0.0765 lb/ft^3 and the air velocity (v) is kept a constant 2 ft/s to find a relatve velocity (v_r). The friction force is computed using the measured 1.3 lbf weight force (N) of the vehicle. For simulation, the coefficient of rolling friction (μ_r) is set to 0.05 to represent the actual interaction between rubber and concrete.

$$F_D = \frac{1}{2}\rho C_d A_S {v_r}^2 \tag{2}$$

$$F_f = \mu_r N \tag{3}$$

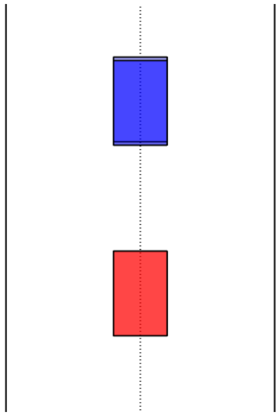

Figure 4. Starting layout for the vehicle blocks used during MATLAB simulations. Motion for Vehicle 1 (red) is actively computed and dependent on the location of Vehicle 2 (blue), detected using ultrasonic wave sensors . Vehicle 2 operates based on preset dynamometer testing data from the EPA.

Vehicle 2 is data-driven vehicle system based upon the United States Environmental Protection Agency's (EPA) dynamometer driving schedules [6]. The EPA publishes vehicle performance for fuel economy and motor vehicle emissions testing publicly to their main site. The EPA uses these data sets to establish trends in vehicle performance, pollution, and fuel consumption based on the behavior of the vehicle in various environments and scenarios. These test cases include highway travel under 60 mph, urban driving schedules, aggressive acceleration driving trends, heavy duty vehicle operation, and stop-and-go travel in New York City. The data provided gives a realistic behavior for motor vehicle and is beneficial for simulating accurate vehicle motion. Specifically, the stop-and-go traffic data in New York City was used to test the performance of MATLAB simulation against real-world travel data. This data also allows the simulation to be tested against sudden stoppage and acceleration from nearby vehicles, a common and dangerous behavior on city streets and roadways. Vehicle 2 uses this data to update its current velocity to the test course while Vehicle 1 reacts to changes in distance between its front bumper and the rear bumper of Vehicle 2.

Results

Test Case 1

The testing simulation is performed over a 10 second time study of 0.1 second increments. A range of Vehicle 1 is instructed to follow Vehicle 1 with an initial driving force of 0.5 lbf when motion is permitted, decelerate when within 2 feet of Vehicle 2, and accelerate further than 10 feet away from Vehicle 2. Vehicle 1 and Vehicle 2 are set at rest within stopping range of one another at the beginning of the simulation. Vehicle 2, which has a controlled, data-driven velocity output, remains at rest for approximately 4.5 seconds of the beginning simulation. The initial and final positions of are shown in Figure 5. Vehicle 1 begins 5 feet away from Vehicle 2 in the simulation environment. Aerodynamic drag force and friction force affect Vehicle 1 with 1 ft/s winds and a rubber to concrete coefficient of drag of 0.05.

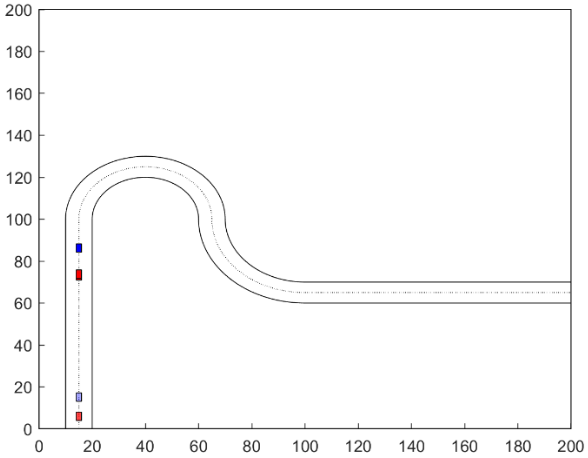

Figure 5. Beginning and ending locations for vehicle simulation with 0.5 lbf starting driving force.

Figure 6 depicts the motion of Vehicle 1 and Vehicle 2 using position, velocity, and acceleration throughout the simulation enviornment. An intersting result is that the simulation shows that Vehicle 1 moves slowly in the beginning time portions even though it is a safe distance away from Vehicle 2. Analysis shows that the 0.5 lbf driving force was not large compared to the aerodynamic drag force and friction force placed on the vehicle. Only once Vehicle 2 was greater than 10 feet away was Vehicle 1 allowed to increase its driving force and catchup to Vehicle 2, overcoming the resistance forces.

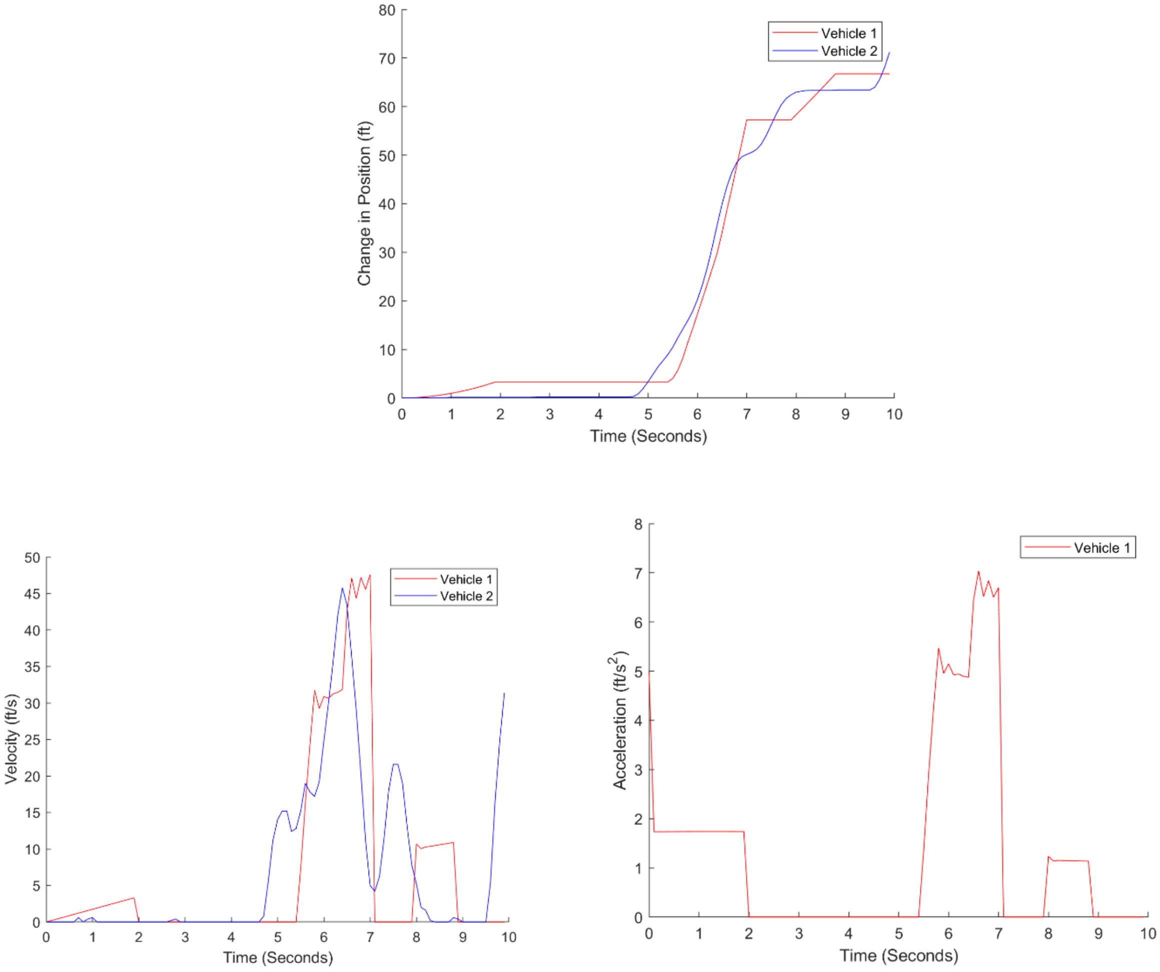

Figure 6. Position (top), velocity (left), and acceleration (right) of Vehicle 1 and Vehicle 2 with an initial 0.5 lbf driving force applied to Vehicle 1.

In order for a collision to occur, the difference between the Vehicle 1 and Vehicle 2 must be less than -5 feet, or the initial starting distance between the two car models. The MATLAB simulation shows that at approximately 7 seconds, a collision occurs between the two vehicles. Due to the low initial drive force, Vehicle 1 continued to accelerate towards Vehicle 2 over time, to a point where the Vehicle could not decelerate in time once it was with 2 feet of the Vehicle 2. This is shown in the drastic change in acceleration occurring between 6 and 8 seconds on the acceleration plot where Vehicle 1 traveled at a speed of over 60 ft/s in an attempt to properly follow Vehicle 2.

Test Case 2

Similar parameters to Test Case 1 are maintained including the time of the study, the data-driven source of Vehicle 2, resistance forces, and the overall test course. However, the initial drive force is increased to 2.0 lbf for Vehicle 1 instead of 0.5 lbf in Test Case 1. This test is implemented as analysis shows that this initial driving force is now large enough to overcome the resistance forces placed on Vehicle 1. Running this simulation, the result initial and final positions of Vehicle 1 and Vehicle 2 are similar to between both Test Case 1 and Test Case 2. This expected for Vehicle 2 as the data provided for vehicle simulation has not been changed, modified, or edited between test cases and still represents the EPA dynamometer testing data for stop-and-go travel in New York City. However, Vehicle 1 also remains in a similar position between both test cases, as shown in Figure 7. This suggests that the simulation algorithm is successful in finding an ideal travel condition for Vehicle 1 over time.

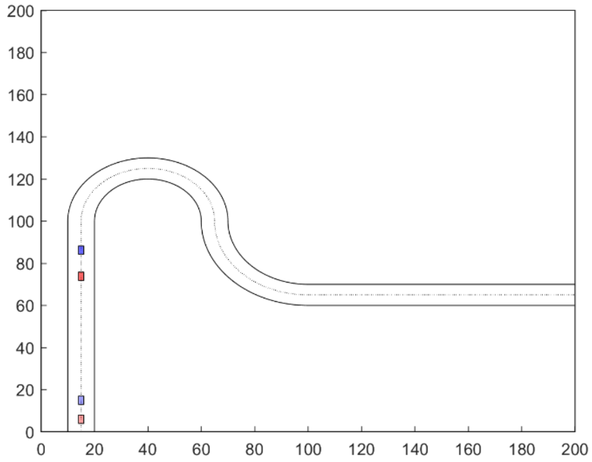

Figure 7. Beginning and ending locations for vehicle simulation with 2.0 lbf starting driving force.

Figure 9 shows that the simulation results show a slight improvement in the overall system. With an increased starting drive force, Vehicle 1 is able to begin motion in the beginning seconds of the simulation until it comes into close contact with Vehicle 2 with approximately 1.4 feet of clearance. Once Vehicle 2 begins to move, Vehicle 1's navigation algorithm is precise enough to remain within 10 feet of Vehicle 2 for a majority of the simulation. However, near the end of the simulation, when Vehicle 2 is instructed to make a sudden stop, Vehicle 1 is unable to fully recover in time. This results in a small collision between the vehicles with the seperation clearance recorded at -5.0 ft, or 0.0 feet between the two vehicle bumpers. This suggests that a 2.0 lbf initial driving force is sufficient for the Vehicle 1's autonomous algorithm to account for Vehicle 2's travel trends, but not more time or clearance is needed to allow time for Vehicle 1 to react to sudden stoppage.

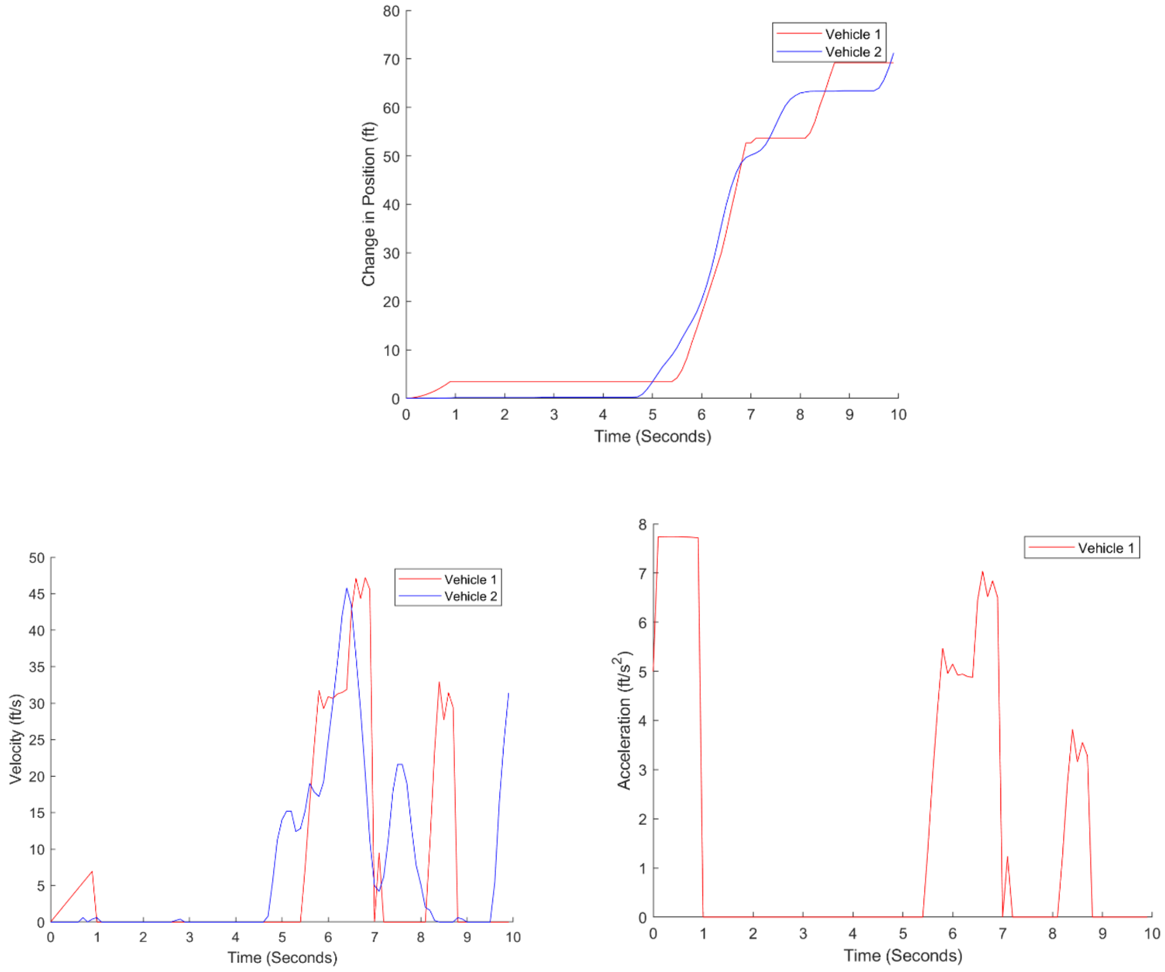

Figure 8. Position (top), velocity (left), and acceleration (right) of Vehicle 1 and Vehicle 2 with an initial 2.0 lbf driving force applied to Vehicle 1.

Test Case 3

Test Case 3 follows the same parameters as Test Case 2 with one change to the vehicle definition. Test Case 2 was found to be a sufficient model for Vehicle 1's navigation, however the model was still susceptible to sudden stoppage events from Vehicle 2. To account for this, Vehicle 1 is now instructed to decelerate when within 4 feet of Vehicle 2 rather than 2 feet used in Test Case 1 and Test Case 2. Figure 9 shows the initial and final locations of both vehicles after the simulation is computed.

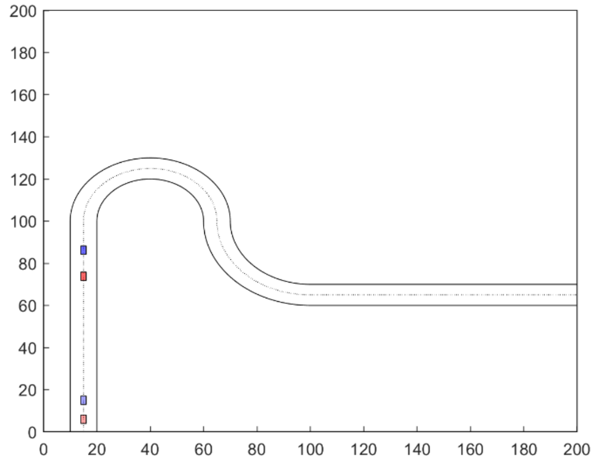

Figure 9. Beginning and ending locations for vehicle simulation with 2.0 lbf starting driving force and an added 2 feet of deceleartion clearance to Vehcie 1.

This test case returns the most promising results. As shown in Figure 10, the initial driving force remains a sufficient starting force to properly drive the vehicle system against the environmental resistance forces. Most promising is the behavior of Vehicle 1 once Vehicle 2 begins to significantly travel down the test course. Vehicle 1's navigation algortihm remains precise enough to follow Vehicle 2, maintaining a reasonable clearance gap of approximately 3 to 6 feet. In addition, no collisions occur in this simulation study. This is due to the increased sensistivity of the ultrasonic wave sensor used for range detection in the front of the vehicle models. With a deceleration clearance of 4 feet, Vehicle 1 now has sufficient room to react and adapt to the travel of Vehicle 2. This is evident in the multiple stopping events along the velocity plot in Figure 10 and two large jumps to 8.6 ft/s^2 and 8.5 ft/s^s during the fastest travel periods of Vehicle 2.

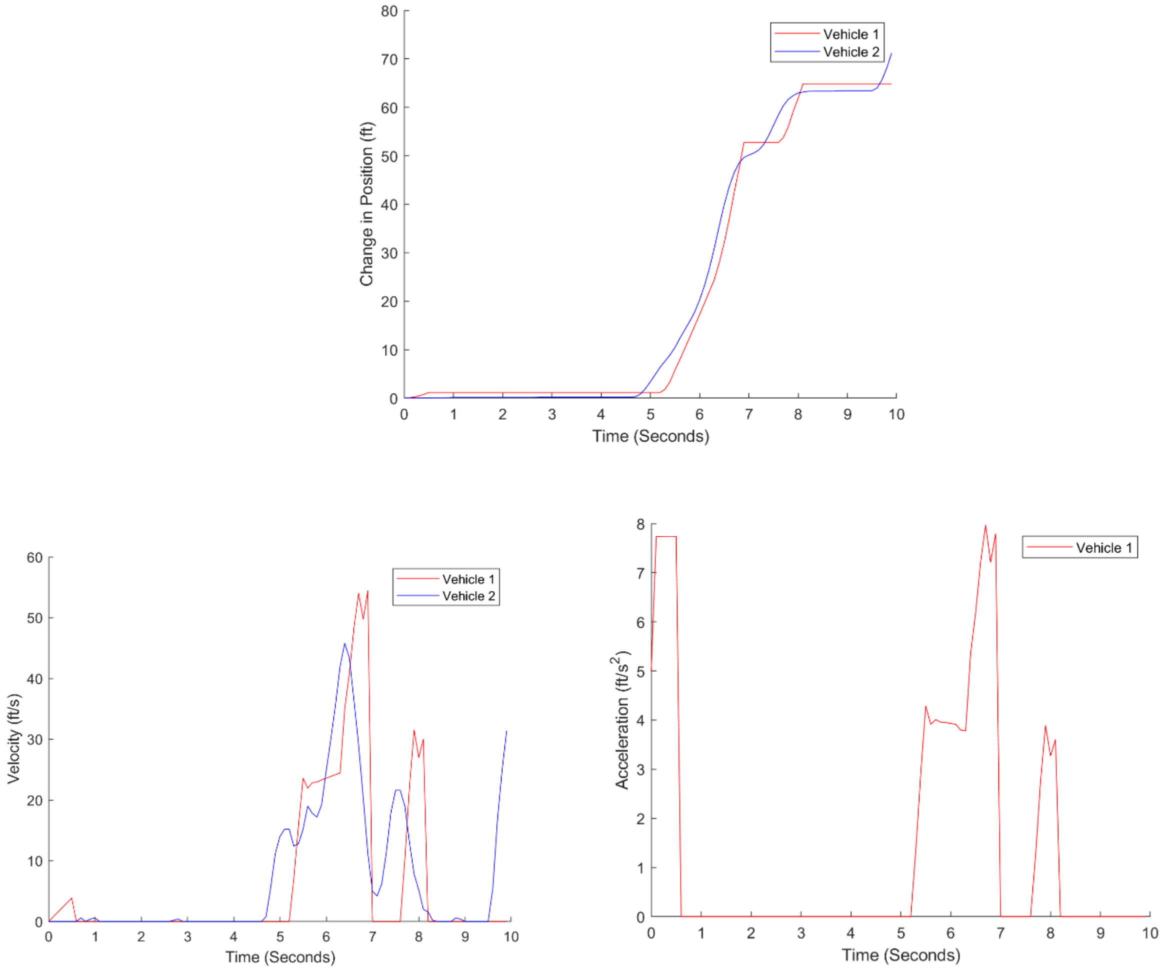

Figure 10. Position (top), velocity (left), and acceleration (right) of Vehicle 1 and Vehicle 2 with an initial 2.0 lbf driving force and additional 2 feet of deceleration clearance for to Vehicle 1.

Conclusion

Autonomous vehicles (AV) are a growing future for the transportation industry. AVs require little to no assistance from the driver and vehicle passengers while removing a prevalent source of vehicle accidents, collisions, and mistakes on the roadways and highways. Human error, an unavoidable component of human-controlled vehicle operation, has been a factor in the deaths and injuries of thousands of vehicle operators. Even in current human-controlled vehicle systems, levels of autonomy such as cruise control and emergency brake technology create safety features that protect the vehicle operator, nearby vehicle operators, and the transportation environment.

The MATLAB simulation algorithm developed showed that it is feasible to incorporate real-world travel data into a scale model simulation environment with vehicle controls applied. This shows a promising application for simulation study for scale model autonomous vehicle applications. The results show that the algorithm's success is heavily dependent on preset conditions such as driving force and clearance gaps. Both conditions can be altered readily and modified in simulations, however limitations for components for real-world applications, such as sensor sensitivity and motor selection, will define the capabilities of the vehicle system. Future adaptations and work to improve the control algorithm for a more diverse set of initial conditions would provide more useful and practical applications for the simulation and real-world hardware application.

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