

Development of a Path-following and a Speed Control Driver Model for an Electric Vehicle

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ABSTRACT

A two-passenger all-wheel-drive urban electric vehicle (AUTO21EV) with four in-wheel motors and an active steering system has been designed and developed at the University of Waterloo. In order to evaluate the handling and performance of such a vehicle in the design stage and analyze the effectiveness of different chassis control systems before implementing them in the real vehicle, the simulation of a large number of different open-loop and closed-loop test maneuvers is necessary. Thus, in the simulation environment, not only is a mathematical vehicle model needed for every test maneuver, but a driver model must also be designed to simulate the closed-loop test maneuvers. The role of the driver model is to calculate the control inputs required to successfully follow a predefined path. Such a driver model can be implemented as an inverse dynamics problem or by a representation of a driver that can look ahead, preview the path, and change the steering wheel angle and acceleration or brake pedal positions accordingly. In this regard, a path-following driver model is developed in this work with an advanced path previewing technique. In addition, a gain scheduling speed control driver model is developed for the AUTO21EV, which adjusts the drive torques of the wheels to minimize the deviation between the desired and actual vehicle speeds.

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INTRODUCTION

The driver of a passenger car is responsible not only for controlling the vehicle speed by actuating the brake and accelerator pedals, but also for controlling the direction in which the vehicle is travelling. Thus, the tasks of the driver are threefold: navigation, path following, and vehicle stability [1]. In order to travel between two points, a driver must first choose a suitable route. Criteria such as route length and travelling time might be used to select the desired route. Navigation systems can help a driver plan a route between two points, but the ultimate decision about which route to select is still made by the driver. The second task of a driver is to define the desired path for the vehicle within the chosen route based on additional information that is gathered along the way, such as traffic conditions, traffic signs, and unexpected obstacles. Despite technical advancements in this area, the path-following task cannot be fully automated using control systems such as path-following cameras or inductive highway striping. The final task of a driver is to keep the vehicle on the desired path using the available actuators (the steering wheel, brake pedal, and accelerator pedal). Moreover, the driver is responsible for the stability of the vehicle while driving through the desired path.

From a control systems perspective, the driver and vehicle can be modelled as a control loop, where the driver acts as a controller that is responsible for the stability of the plant, which is the vehicle (Figure 1). In such a control loop, some disturbances act on the driver (such as the relative motion between the vehicle and the driver, driver distractions, and line-of-sight obstructions), and others act on the vehicle (such as cross wind, different coefficients of friction on the road, and road roughness). In terms of the lateral dynamics, the actuating variable that must be corrected by the driver is the steering wheel angle; in terms of the longitudinal dynamics, the actuating variables are the brake and accelerator pedal positions. The control deviation that must be corrected by the driver in the lateral dynamics domain is the difference between the desired and actual paths, while in the longitudinal dynamics domain, the deviation between the desired and actual speeds must be corrected. Moreover, the driver-vehicle-environment control loop is considered to be a dynamic closed-loop system, whose stability depends mostly on the vehicle behaviour and the capabilities of the driver. In other words, the stability of this control loop depends on the ability of the controller (the driver) to handle large errors, the behaviour of the control system under fast control actions,

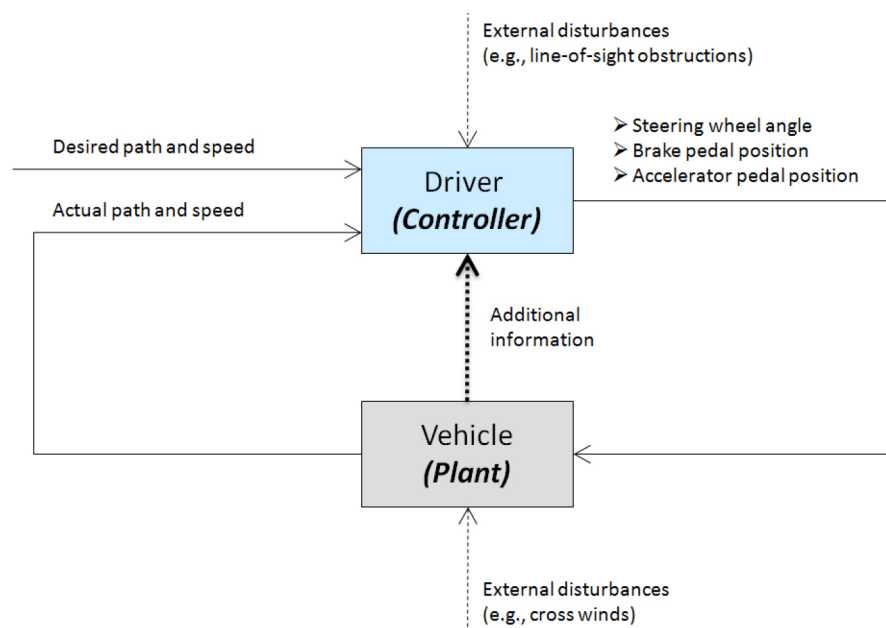


Figure 1. Graphical representation of the driver-vehicle-environment control loop

and the stability of the system under the influence of external disturbances. In general, the dynamic characteristics of the vehicle must match the capabilities of the driver. The quality of this match defines the vehicle handling and performance characteristics. In this regard, a vehicle is considered to have a good handling characteristic if the following arguments are true [1]:

- There must be a good correlation between the steering wheel variation and the lane-change behaviour of the vehicle. This property defines the transfer function behaviour of the vehicle as the plant of the control loop.
- The driver must receive reasonable information about the condition of the vehicle in order to predict its behaviour. For instance, changes in the steering wheel feedback torque, the vehicle sideslip angle, and tire squeak before reaching the physical limit of adhesion will all help the driver predict the behaviour of the vehicle and, ultimately, react correctly.
- The external disturbances acting on the vehicle should cause little or no change in the course of the vehicle - that is, the vehicle should be inherently stable.
- The vehicle must have a high lateral acceleration limit, which defines the lateral stability reserve of the vehicle; the larger this limit, the more stable the vehicle will be.

It is important to note that there are no standard legal regulations about the vehicle handling and performance characteristics, and every car manufacturer is free to set its own specifications in this area. Looking at the vehicle handling and performance from the driver's perspective, it is a completely subjective evaluation that can change from one driver to another. Therefore, it is very difficult to set a standard criterion for quantifying the quality of these

evaluations. In fact, there is no comprehensive, objective definition for the dynamic characteristics associated with the driver-vehicle-environment control loop, as adequate data on the precise control characteristics of the human element are still not available [2]. For this reason, in practice, the assessment of the vehicle is performed by expert drivers who can subjectively evaluate the measured data gathered through a series of standard test maneuvers.

Figure 2 illustrates the AUTO21EV, which is a two-passenger all-wheel-drive urban electric vehicle developed and modelled in this work using the ADAMS/View environment. This vehicle has a similar configuration to the commercially available Smart *fortwo*, but it is equipped with four direct-drive in-wheel motors and an active steering system on the front axle. Further details about AUTO21EV can be found in [3]. In order to evaluate the handling and performance of the AUTO21EV and analyze the effectiveness of different chassis control systems before implementing them in the real vehicle, the simulation of a large number of different test maneuvers is necessary. In this regard, in the simulation environment, not only is a mathematical vehicle model needed for every test maneuver, but a driver model must also be designed to simulate the closed-loop test maneuvers.

DIFFERENT TEST MANEUVERS FOR EVALUATING VEHICLE HANDLING AND PERFORMANCE

Many test maneuvers have been developed for evaluating the quality of the handling and performance characteristics of a vehicle. Many of these test maneuvers are based on ideal driving conditions, and some of them are motivated by the

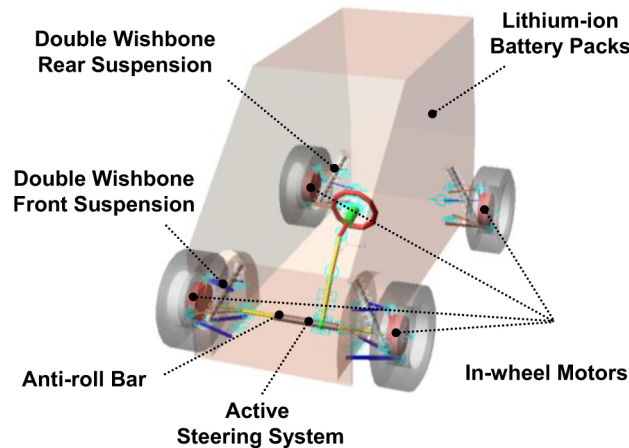


Figure 2. AUTO21EV concept vehicle

Driving Situation	Test Maneuvers	Closed-loop	Open-loop
Cornering Events	Steady-state constant radius cornering	N	Y
	Load-cycle changes	Y	Y
	Transient constant radius cornering	Y	Y
	Braking-in-turn	Y	Y
	Aquaplaning (μ -split road)	Y	Y
Straight-line Events	Directional stability	Y	Y
	Straight-line acceleration	Y	Y
	Aquaplaning (μ -split road)	Y	Y
	Straight-line braking	Y	Y
	Cross wind	Y	Y
	Load-cycle changes	Y	Y
	Responsiveness test	Y	N
Dynamic Performance Tests	Step-steer	N	Y
	Impulse-steer	N	Y
	Single-lane-change	Y	N
	ISO double-lane-change	Y	N
	Driving in a curve	Y	N
	Driving out of a curve	Y	N
Transient Behaviour Tests	Sine steer	N	Y
	Swept-sine steer	Y	N
	Step-steer and acceleration	N	Y
	Obstacle avoidance test	Y	N

Figure 3. Different test maneuvers for evaluating vehicle handling and performance characteristics [4] (Y = yes and N = no)

examination methods typically used for control systems, such as step-steer and swept-sine-steer maneuvers (Figure 3). An extensive overview of different test maneuvers and their detailed descriptions can be found in the publications of Roenitz, Braess, and Zomotor [4, 5].

The test maneuvers that describe the vehicle behaviour in terms of the driver-vehicle-environment control loop are known as 'closed-loop' test maneuvers. To evaluate these maneuvers, the quality of the match between the dynamic behaviour of the vehicle and the driver's capabilities must be considered. These test maneuvers require a professional driver who can make judgments on the handling qualities of the vehicle based on the combination of diverse subjective impressions. In the simulation environment, an appropriate

driver model is used simulating the required behaviour of a specific driver (professional or average driver) in following a desired predefined path, in place of a test driver.

On the other hand, if the actuation variables in a test maneuver are defined to be pure functions of time, and the dynamic behaviour of the vehicle has no influence on the driver's response, then the test maneuver is known as an 'open-loop' maneuver. In an open-loop test maneuver, the driver is replaced by a specific, objectively quantifiable interference factor, and the handling data derived from the maneuver provides objective information about the handling qualities of the vehicle. Open-loop test maneuvers also provide insight into the stability of the vehicle and the sensitivity of the vehicle to external disturbances. In

summary, each test maneuver provides some information about the dynamic behaviour of the vehicle in one or several respects, such as vehicle handling, stability, path following, and longitudinal dynamics. Therefore, a comprehensive evaluation of the dynamic characteristics of a vehicle is only possible by examining the results obtained from several different test maneuvers.

MODELLING THE BEHAVIOUR OF A DRIVER

In order to evaluate the handling and performance of the vehicle in the design stage and the effectiveness of different chassis control subsystems before implementing them in a real vehicle, the simulation of a large number of different maneuvers is necessary. As discussed earlier, there is a significant difference between open-loop test maneuvers, which are defined by chronological control inputs and are routinely used for the subjective evaluation of handling performance, and closed-loop test maneuvers, which primarily involve a path-following task. However, in order to realize these test maneuvers in the simulation environment, not only is a mathematical vehicle model needed for every test maneuver, but a driver model must also be designed to simulate the closed-loop test maneuvers. The role of the driver model is to calculate the control inputs required to successfully follow a predefined path. Such a driver model can be implemented as an inverse dynamics problem [6] or by a representation of a driver that can look ahead, preview the path, and change the steering wheel angle accordingly [7, 8].

There exist a variety of controllers suitable for modelling driver behaviour, some of which are more complex than the others. Therefore, one should first choose the level of modelling fidelity required to achieve the task at hand, based on the needs of the simulation. In general, driver models fall into two main categories: optimum control models and moment-by-moment feedback models [9]. Optimum control models use some form of penalty function as a measure to assess the quality of the control achieved. These models use repeated simulations of a specific event and numerical optimization methods to tune the parameters of the driver model such that the value of the defined penalty function is minimized over the duration of the event of interest. Although optimum control models are suitable for learned events, such as the circuit driving of race cars, some care must be exercised with their use for evaluating the performance of regular passenger cars. Since the average driver of a passenger vehicle is generally unskilled, the application of modelling techniques in which repeated simulations are used to discover the so-called 'best' way of achieving a maneuver may not be an appropriate way of simulating an emergency situation, where the driver has only one attempt to complete the maneuver [7, 10]. Moment-by-moment feedback models are a subset of the optimum control models, with the difference being that the feedback

parameters of the controller are set once by the analyst and remain constant thereafter. Although these models are less appropriate for predicting the driver behaviour for circuit racing, they add clarity in understanding the vehicle behaviour and driver inputs when driving through a test maneuver [11]. Such driver models are also more appropriate for understanding the effects of different chassis control systems on both the vehicle and the driver when driving through closed-loop test maneuvers.

DEVELOPMENT OF A PATH-FOLLOWING DRIVER MODEL

With these facts in mind, a moment-by-moment feedback driver model that is similar to the model described in [8] is developed in this work, but is enhanced with a more sophisticated path previewing technique. The driver model described in [8] uses a single-preview-point steering control model, whose objective is to steer a ground vehicle along a reference line located in the middle of the lane to be followed. In this regard, a single arbitrary look-ahead point is defined along the local longitudinal axis of the vehicle, and the distance between the look-ahead point and the reference path is defined as the "look-ahead offset". The required steer angle is then calculated as a function of the look-ahead offset, vehicle longitudinal velocity, and various vehicle parameters. A linear bicycle model is used, as illustrated in Figure 4, to obtain the following linear state-space equation [8]:

$$\begin{bmatrix} \dot{v} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{-C_{af} + C_{ar}}{m_{CG} \cdot u} & -u + \frac{b \cdot C_{ar} - a \cdot C_{af}}{m_{CG} \cdot u} \\ \frac{b \cdot C_{ar} - a \cdot C_{af}}{I_z \cdot u} & -\frac{a^2 \cdot C_{af} + b^2 \cdot C_{ar}}{I_z \cdot u} \end{bmatrix} \cdot \begin{bmatrix} v \\ r \end{bmatrix} + \begin{bmatrix} \frac{C_{af}}{m_{CG}} \\ \frac{a \cdot C_{af}}{I_z} \end{bmatrix} \cdot \delta \quad (1)$$

where u , v , and r are, respectively, the longitudinal, lateral, and yaw rate vectors of the vehicle, and $u = |\vec{u}|$, $v = |\vec{v}|$, and $r = \dot{\psi} = |\vec{r}|$ are the magnitudes of these vectors. In addition, a and b are the distances of the front and rear axles to the vehicle center of gravity, m_{CG} is the vehicle mass, I_z is the yaw moment of inertia, δ is the steering angle of the front wheel, and C_{af} and C_{ar} are the total cornering stiffnesses of the front and rear tires, respectively. As illustrated in Figure 4, $\vec{V}$ indicates the velocity vector of the vehicle's center of gravity, whose magnitude is $V = |\vec{V}| = \sqrt{u^2 + v^2}$. Note that the vehicle coordinate axes are in accordance with the ISO 4130 and DIN 70000 standards, where the Z direction points upwards, the X-axis is along the vehicle longitudinal axis and points towards the front of the vehicle, and the Y-axis points left when viewing along the positive X direction.

Figure 5 illustrates the vehicle motion along a desired circular path of radius R , where the distance between the

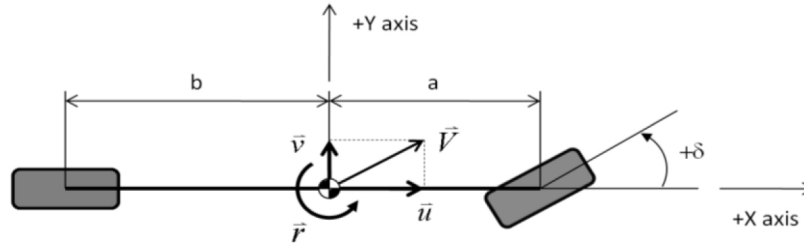


Figure 4. Linear bicycle model used for developing the driver model

center of gravity of the vehicle and the look-ahead point is defined as look-ahead distance d , the distance between the look-ahead point and the point on the curve closest to it is defined as look-ahead offset o , and the distance between the look-ahead point and the center of the curve is defined as h . By considering the steady-state motion of the vehicle along the curve, where the vehicle perfectly tracks the desired path, explicit expressions are obtained for the variables v_{ss} , r_{ss} , V_{ss} , δ_{ss} , o_{ss} , and h_{ss} . All of these expressions are in terms of the vehicle longitudinal speed u , the radius of curvature R , and the vehicle parameters. Note that the subscript 'ss' indicates that the values are calculated when the vehicle is in a steady-state condition, where $\dot{v} = \dot{r} = 0$, the center of gravity of the vehicle perfectly tracks the desired curve, the velocity vector V is tangent to the curve, and the longitudinal velocity u is held constant. At steady-state, equation (1) becomes the following:

$$-\begin{bmatrix} \frac{-C_{af} + C_{ar}}{m_{CG} \cdot u} & -u + \frac{b \cdot C_{ar} - a \cdot C_{af}}{m_{CG} \cdot u} \\ \frac{b \cdot C_{ar} - a \cdot C_{af}}{I_z \cdot u} & -\frac{a^2 \cdot C_{af} + b^2 \cdot C_{ar}}{I_z \cdot u} \end{bmatrix} \cdot \begin{bmatrix} v_{ss} \\ r_{ss} \end{bmatrix} = \begin{bmatrix} \frac{C_{af}}{m_{CG}} \\ \frac{a \cdot C_{af}}{I_z} \end{bmatrix} \cdot \delta_{ss} \quad (2)$$

From equation (2), the steady-state lateral velocity (v_{ss}) can be calculated as a function of the steady-state yaw rate (r_{ss}) as follows [8]:

$$v_{ss} = T \cdot r_{ss}, \text{ where } T = b - \frac{a \cdot m_{CG} \cdot u^2}{C_{ar} \cdot (a + b)} \quad (3)$$

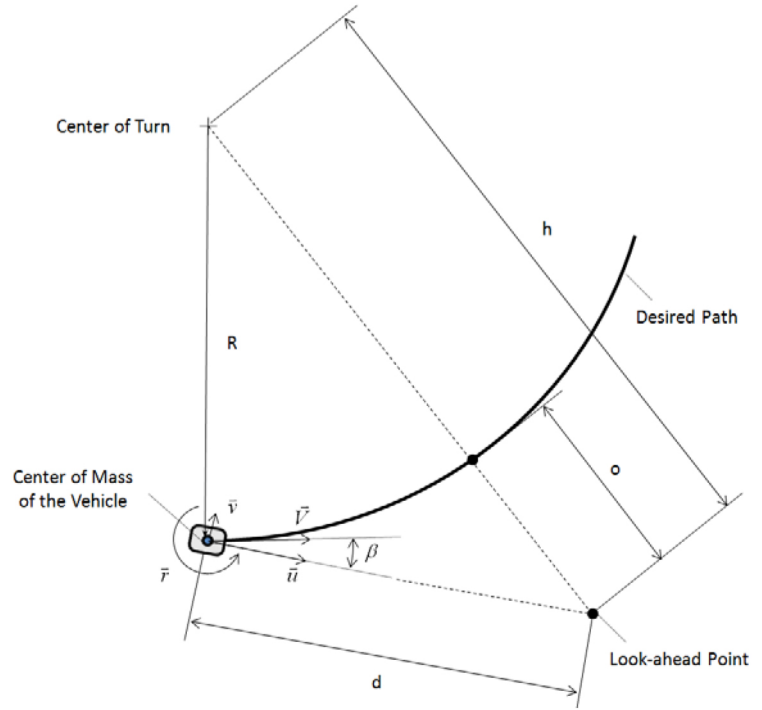


Figure 5. Steady-state vehicle motion along a circular path of radius R

In general, the following statements can be made for a vehicle in steady-state circular motion [8]:

$$V_{ss} = \sqrt{u^2 + v_{ss}^2} \quad (4)$$

$$V_{ss} = R \cdot r_{ss} \quad (5)$$

One can now obtain new expressions for r_{ss} and δ_{ss} from equations (2), (3), (4), (5) that are only in terms of the vehicle longitudinal speed u , the radius of curvature R , and vehicle parameters [8]:

$$r_{ss} = \frac{u}{\sqrt{R^2 - T^2}} \quad (6)$$