Abstract—This paper describes an automatic steering controller based on a target and control driver steering model. Derived based on analyses of vehicle test data on the standard Double Lane Change (DLC) course, this novel target and control driver model captures driver’s key steering mechanisms. The analyses show that, instead of planning and following a desired path according to the traditional trajectory planning concept, drivers use the next lane center as the target points to generate vehicle angle error for control during lane changes. The data also suggests that drivers apply steering rate control instead of the conventional steering angle control to steer the vehicle. By extending this relatively straightforward look-ahead based driver steering model to an automatic steering controller with a “look-down” sensing system, an equivalent controller structure was derived. The structure revealed that drivers apply a PID-type controller whose look-ahead distances and feedback gains are dependent on the vehicle speed. This equivalent controller was directly implemented on a 60-ft articulated bus for revenue service on a narrow and curving bus rapid transit line at Eugene, Oregon, USA. The field tests demonstrated that the controller achieved all the stringent performance and robustness requirements. This automated steering bus started its daily revenue service (i.e., carrying passengers) started in June, 2013.

I. INTRODUCTION

Research in automated vehicles has been continuously advanced for over fifty years [1, 2]. Many different sensing methods have been explored and improved for lateral control. These sensing methods can be categories into the look-ahead and the look-down systems [3]. The look-ahead sensing systems, such as radar, LIDAR, and cameras, measure the lateral displacement in front of a vehicle; while the look-down systems, including magnetic markers and DGPS, look at the distance in the close vicinity of the vehicle. In the past few years, various improvements have been made for many of the look-ahead sensing systems.

The recent announcements of the autonomous car productions seem to suggest that the automatic steering control is a solved problem. Various steering controllers have been applied in the autonomous applications [4, 5]. Most of them are based on the path tracking methods that control a vehicle to follow a predetermined path. Examples of the path tracking methods include modifications and combinations of Stanley method [4], pure pursuit [6], and (kinematic and dynamic) model based controllers [7, 8]. Although these path-tracking methods can perform quite well in many operational scenarios, practical applications that demand high accuracy and robustness often remain challenging [9]. This paper presents such an application, where the automatic steering control system needs to provide lane keeping and precision docking for a 60-ft articulated bus in revenue service (carrying passengers) along a narrow (typically 10 ft wide) and curving segment of the EmX Bus Rapid Transit (BRT) route of Lane Transit District in Eugene, Oregon. This particular segment was chosen for automatic steering control because driving through this corridor has been a challenge for operators, which results in high turnover. Moreover, the transit agency experienced relative large amount of tire damages as the tires frequently touch the curb and platform guard under manual control.

Excluding the docking S-curves, this 3-mile segment (1.5 miles in each direction) contains 36 curves; 8 of them have radii less than 100 m (the smallest is 46 m). Five of the six stations for precision docking involve sharp S-curves (with radius less than 40 m), and most stations have limited docking spaces confined by the platform and the curb. Fig. 1 illustrated one station where the 60-ft (18.3m) articulated bus needs to make a full lane change and immediately pull straight, all within the distance of two and a half of the bus length. To make this particular control problem more difficult, the driver is in charge of controlling the accelerator and brake. The data showed that the bus reached speeds above 40 mph (64.4 km/h) in this narrow corridor, and some of the sharp S-curve dockings were maneuvered at speeds above 20 mph (32.2 km/h). In addition, the drivers could perform an emergency braking when the bus is next to the platform. All these challenging operating scenarios require the steering controller to consistently maintain high accuracy (and ride comfort) under any weather and operational condition.

![Figure 1. Walnut Stations (west- & east-bound) docking S-curves](image-url)

On the other hand, without the help of sophisticated sensors or precision actuators, and without the clear knowledge of the vehicle parameters, most passenger-car drivers perform the daily steering tasks with ease. One possible reason that most steering controllers in practice...
seem to have difficulties in reaching performance potential suggested by drivers could be that the typical path-tracking methods miss some essence of how drivers steer. In a recent study, vehicle data from Double Lane Change (DLC) tests indicated a relatively simple driver steering mechanism, and the closed-loop simulation results were able to match the vehicle test data from 20 drivers of various driving skill levels [10]. The essence of this driver steering mechanism is “target and control”: that is, instead of planning and following a specific trajectory, drivers simply apply steering rate control based on a specific vehicle angle error with respect to a (moving) target ahead. Further synthesis of this mechanism revealed two characteristics that help explain why drivers perform the steering tasks with ease. The controller generates two desirable zeroes for high-gain stability, and the natural choices of the control parameters create an inherently insensitive structure to vehicle dynamics and speeds. These findings motivated the development of a new steering controller for our application based on this driver steering model.

The paper is organized as follows. Section II reviews the development of this target and control driver steering model based on the DLC vehicle test data. Section III transforms this simple driver model to an equivalent control structure implementable with look-ahead or look-down sensing systems. Section IV sketches the steering controller design using the equivalent control structure. Section V describes the implementation of this controller and presents the field test results demonstrating that the system has achieved all the performance and robustness required by the revenue service. Section VI concludes the paper.

II. TARGET AND CONTROL DRIVER MODEL

The Target & Control (T&C) steering mechanism was discovered by examining data from the DLC maneuver. As validated in [10], drivers select the target points located along the centerline of the lane they are changing to as the references for the lane-change control. As shown in Fig. 2, the DLC course can be divided into three sessions by the two transition points A and B, which are the locations where a driver begins his/her lane change to the next lane.

![Figure 2. DLC Target sets (dotted line along the lane centerline)](image)

When the vehicle travels before the Transition Point A, the targets lie on the centerline of the lane defined by the first cone set. At this stage, the driver is performing a lane-keeping maneuver. When the vehicle is between Points A and B, the driver selects the targets along the centerline defined by the second cone set and conducts a lane-change maneuver without explicitly planning a trajectory on the ground. For the second lane change, the driver immediately switches to a new set of targets lying on the centerline defined by the third cone set once he/she passes Point B.

Therefore, at any time instance, the target point is at a (variable) look-ahead distance away from the vehicle position. Thus, given Points A and B and a look-ahead distance \( d(t) \), the preview target \( T(x_T(t), y_T(t)) \) can be determined based on the current vehicle position \( (x(t), y(t)) \):

\[
\begin{bmatrix}
x_T(t) - x(t) \\
y_T(t) - y(t) \\
\end{bmatrix} = d(t) \quad \text{and} \quad \begin{bmatrix} x_T(t) \\ y_T(t) \end{bmatrix} \in \mathcal{I}
\]

where \( \mathcal{I} \) is the centerline of the lane which the vehicle is changing to. In this DLC maneuver, \( \mathcal{I} \) is a function of the vehicle current position \( (x(t), y(t)) \) and the transition locations A and B.

With a given target, the control action is then determined using the target heading angle described below. Given the vehicle current position \( (x(t), y(t)) \), yaw rate \( \omega(t) \), speed \( v(t) \), and a target \( T (x_T(t), y_T(t)) \), and assuming the vehicle maintains its current yaw rate \( \omega(t) \) and speed \( v(t) \), the target heading angle \( \theta_T \) is the heading angle that ensures the vehicle reaches target \( T \). Therefore, the target heading angle is the desired heading angle and the goal of the steering controller is to reduce the difference between the actual vehicle heading angle and the target heading angle. Thus, this vehicle angle error is defined as:

\[
\theta_e(t) = \theta_T(t) - \theta_p(t)
\]

Fig. 3 illustrates two target heading angles (i.e., the desired vehicle angles), \( \theta_T \) and \( \theta_{T1} \), corresponding to two targets \( T \) and \( T_1 \), respectively. The vehicle maintains its current yaw rate \( \omega(t) \) and speed \( v(t) \) while traveling toward the target point. Thus, the blue lines are curves with the same fixed radius: \( R(t) = v(t)/\omega(t) \).

![Figure 3. Target heading angles](image)

One important finding in [10] was that, regardless of the skill levels and speeds, the steering angle rates of all 20 drivers were proportional to the target heading angle error. Fig. 4 clearly illustrates this proportional relationship for an expert driver and a low-skill driver (as highlighted in the shaded areas). The dotted lines are the computed target angle errors with respect to targets at 15, 18, 21, and 24m look-ahead distances. Comparing the steering angle rate to the dotted lines revealed the most likely look-ahead distance used by the driver when he/she was conducting the respective lane change.

![Figure 4. DLC Analysis: steering rate vs. vehicle target angle error](image)
The discovery suggested a linear steering rate control:
\[
\dot{\delta}(t) = k \theta_e(t) \tag{3}
\]
The data indicated that each driver has his/her own value of \(k\), which is roughly proportional to the ratio of speed over the look-ahead distance. The data analyses further suggested that most drivers employed some straightforward gain-scheduling schemes that would increase the control gain whenever the target angle error became too big. This seems to be a common driver behavior. This gain scheduling scheme is described in Eq. (4) below:
\[
k = k_i \text{ for } e_i \leq |\theta_d| < e_{i+1}. \tag{4}
\]
Typically, \(i\) starts from 0 and ends at either 2 or 3, and \(e_0\) is 0. Closed-loop simulations showed that a couple of steps of gain scheduling were often what it took to achieve a good match between the simulation results and the vehicle test data. Fig. 5 shows the good matches between the closed-loop simulation using the CarSim vehicle model and the test data for the two drivers shown in Fig. 4. The closed-loop simulations did not use any vehicle test data except speed, which is critical in verifying the causality and validity of the identified driver model. Two constant look-ahead distances, 18m and 24m, were chosen for the expert and the low-skill driver, respectively.

![Figure 5. DLC Analysis: T&C (CarSim) simulation vs. test data Expert (left) and Low-skill (right) drivers](image)

The following statements summarize the T&C driver steering model. Instead of planning a trajectory, drivers first select preview targets at a look-ahead distance ahead along the lane they are following or changing to. Drivers then perceive the associated target angle error based on a straightforward geometric relationship. Finally, drivers complete the closed-loop control by employing a linear steering rate control with a few steps of gain scheduling when needed.

### III. Transformation of the T&C Model

The T&C driver steering model can be implemented directly as a T&C controller using Eqs. (1-3), where the vehicle target angle \((\theta_T)\) in Eq. (2) is computed based on the geometric relationship between the current and future road curvature \(\rho_{road}\) and the current vehicle yaw rate \(\dot{\omega}_v\). However, to implement this look-ahead control scheme using look-down sensors, it is first transformed into a conventional lane-keeping control framework. As detailed in [11], the target \(T\) can be obtained using \(\rho_{road} \cdot \dot{\omega}_v\), as well as the current lateral displacement \(y_r\) and a look-ahead distance \(d\). By using the common small angle assumptions, the T&C controller is transformed into an equivalent conventional lane-keeping controller as:
\[
\delta = k \theta_e = k \left( \frac{d}{2} \rho_{road} - \frac{y_r}{\rho_{road}} + \frac{d}{2v} \omega_v + \theta_T \right). \tag{5}
\]

![Figure 6. The equivalent closed-loop diagram of the T&C model](image)

Fig. 6 shows the equivalent locally linearized closed-loop diagram of this T&C control scheme \((G_p\text{ is the vehicle dynamics).}\) It is clear that the vehicle angle error \(\theta_e\) consists of the contributions from the lateral displacement \(\frac{y_r}{d}\), the current vehicle lateral angle with respect to the road \(\theta_T\), the predicted angle error calculated by the road curvature \(\frac{d}{2} \rho_{road}\), and the current vehicle yaw rate \(\frac{d}{2v} \omega_v\).

By using the various relationships among \(\omega_v, \dot{\omega}_v, \theta_e, \) and \(y_r\) as illustrated in Fig. 6, we can further transform Eq. (5) to Eq. (6) as follows:
\[
\delta = -\frac{k}{v} \left( \frac{y_r}{d} \right) y_r + \frac{d}{2v} \theta_T. \tag{6}
\]
Eq. (6) can be further arranged to be:
\[
\delta = \frac{k}{v} \left( \frac{y_r}{d} \right)^2 \tag{7}
\]

According to Eqs. (1-3) of the T&C driver steering model, driver modulates how fast or how slow he/she should correct the steering angle based on the perceived vehicle angle error. Eqs. (6) and (7) further indicate that, in the sense of lane-keeping control, drivers implicitly execute a PID control where the control parameters are determined by the chosen look-ahead distance as well as the vehicle speed. Moreover, a pair of open-loop zeroes appear at \((\frac{y_r}{d} \pm \frac{v}{d} i)\), they have a fixed damping ratio of 0.707 regardless of the vehicle speed and look-ahead distance. This pair of open-loop zeroes help safeguard against the instability created by the higher gain feedback. This explains why drivers often exhibit rather robust steering characteristics, even when they temporarily increase the control gain to avoid crossing the lane boundary or an obstacle. This property makes Eq. (6) a good choice for the baseline high-performance steering controller.

By selecting the look-ahead distance proportional to the vehicle speed (as drivers do most of the time), the controller in Eq. (6) and (7) becomes a linear time varying controller with certain invariant characteristics. This property further enables drivers to easily steer the vehicle at a wider range of speeds. Based on these potential advantages, Eq. (6) is chosen as the “baseline” steering control law for the challenging automated bus revenue operations.

### IV. Design of the Automatic Steering Control

The automatic steering system adopts magnetic sensing technology, in which magnetometers mounted on the bus measure the magnetic field strength of magnetic markers installed under roadway and the lane position is determined based on the measured magnetic field strength. With two embedded magnetometer sensor bars installed (5m apart) under the bus, \(y_r\) and \(\theta_T\) can be derived based on the two lateral deviation measurements. The design of the equivalent
automatic steering controller in Eq. (6) then involves the selections of the appropriate control gain $k$ and the look-ahead distance $d$ so that the closed-loop system would satisfy the performance and robustness requirements of the revenue service along this challenging corridor in Eugene, Oregon. This section describes the relatively straightforward model-based design process for such selections.

With the speed controlled by the driver, the automatic steering control system is to provide both the lane keeping and the precision docking for a 60-ft articulated bus on Franklin EmX BRT route of Lane Transit District (LTD). Since the automated bus will carry paying passengers for an extensive period of time, the two core requirements for the control system design are performance and safety under all possible operational situations. The system safety and the corresponding redundancy design are discussed in [12]; this paper focuses on the design to achieve the performance requirements.

For the automated bus operations, the performance requirements include accuracy, robustness and ride comfort. Eq. (7) is chosen to be the baseline controller because of its intrinsic robustness property as well as its natural ability to sustain the high gain feedback. These two important characteristics facilitate the steering controller to achieve repeatable precision docking at various speed and weather conditions without ever touching the platform or curb.

According to Americans with Disability Act (ADA), the horizontal gap between docking station and vehicle floor shall be no greater than 7.62cm. This translates to a standard deviation (STD) of docking error to be less than 1.27 cm despite of variations in driver’s speed profile. In addition, to allow the 8.5-ft wide bus to travel along a 10-ft narrow lane, the lane keeping accuracy shall have a STD less than 7.6 cm. Moreover, for some curves, the front wheel is steered closer to one side of the curb in order for the rear wheel not to touch the curb (as will be seen in Figs. 12 and 13).

The ride quality requires that the lateral acceleration shall be no greater than 0.12g more than the vehicle speed (m/s) squared divided by the curve radius (m) of the road and the lateral jerk shall be no greater than 0.24 g/s for transit systems with only seated passengers [13]. In terms of its corresponding control requirements, the dominant closed-loop poles of the resultant system should have good damping characteristics.

Once the performance requirements were decided, the next step was to derive the bus model for the model based design. The dynamic model of a 60-ft articulated bus (illustrated in Fig. 7) can be developed based on Kane’s equation [14]. With small angle assumptions (steering angle and articulation angle), the lateral dynamics of an articulated bus can be written as:

$$M \ddot{q} + D \dot{q} + Kq = E_1 \rho + E_2 \delta$$  

(8)

where $q = [y_r \ \ \theta_r \ \ \theta_a]^T$ and $y_r$ represents the lateral displacement of the bus front section CG with respect to the lane center line, $\theta_r$ is the yaw angle of bus front section with respect to the lane center line, and $\theta_a$ is the articulation angle shown in Fig. 7. $\rho$ is the road curvature and $\delta$ is the front wheel steering angle. The matrix $M$ consists of the masses and moments of inertia of the bus front and articulated sections, $D$ includes parameters computed by the tire stiffness and geometric distances, elements in $K$ are basically spring factors from the stiffness of all the tires, and $E$ consists of various nonlinear parameters from all t above numbers. By choosing $x = [y_r \ \ \theta_r \ \ \theta_a \ \ \dot{y}_r \ \ \dot{\theta}_r \ \ \dot{\theta}_a]^T$ as the state, steering angle $\delta$ as the control input, the lateral dynamics of the articulating bus can be written in the state space as:

$$\dot{x} = Ax + B\delta + E\rho + n$$  

(9)

Where

$$A = \begin{bmatrix} 0 & I \ -M^{-1}K & -M^{-1}D \end{bmatrix}, B = \begin{bmatrix} 0 \ M^{-1}E_2 \ M^{-1}E_1 \end{bmatrix}, E = \begin{bmatrix} 0 \ M^{-1}E_1 \end{bmatrix},$$

and $n$ represents the disturbances.

Once the bus model in Eq. (9) is validated, it was used to calculate the locations of the closed-loop poles for sets of predetermined ranges of the look-ahead distance ($d$) and feedback gain ($k$) for all possible speeds ($v$). The next step was to (iteratively) determine the best pair of $k$ and $d$ for each speed $v$ by examining the resultant pole locations based on the prescribed performance criteria. The criteria include the gain margins, the phase margins, the minimum damping of the dominant poles, as well as the theoretical largest tracking errors based on the speed and the road radii. Fig. 8 shows the resultant “optimal” pairs selected for the control gain ($k$) and look-ahead distance ($d$) for the controller in Eq. (7) for the automated articulated bus.

The values in Fig. 8 were then implemented as the nominal control parameters. The above design process ensures that these feedback gains can be increased (via simple gain scheduling) whenever the current or predicted errors become large. As a result, despite the large variations in drivers’ speeds, high accuracy was consistently achieved without any part of the bus ever touching stations or curbs at tight curves, which has been a major cause for the tire damages under manual driving as well as a main cause of driver stress on the challenging EmX route.

V. IMPLEMENTATION OF T&C CONTROLLER FOR AN AUTOMATED BUS IN REVENUE SERVICE

The automatic steering controller was implemented on a 60-ft articulated bus. As shown in Fig. 9, the system consists of two control computers and two Human Machine Interface
(HMI) units for redundancy, a steering actuator (with a DC motor mounted on the steering column) and embedded processor, two embedded magnetometer sensor bars, a yaw rate gyro, and redundant power suppliers (as detailed in [12]). Except the two sensor bars, the steering actuator mechanical assembly, and the LED lights, buzzers, and switches/buttons, all other components were installed on one shelf in the instrument cabinet (9”x6”x15”).

![Figure 9. The automated steering system for New Flyer 60’ bus](image)

Before the bus was tested along the EmX route (public roadway), it went through a complete system testing at the test track in the LTD maintenance yard (Fig. 10) to ensure that the system had achieved all required performance. Multi-layer functional and multi-period reliability testing was then conducted along the EmX corridor to establish the baseline performance and to verify the reliability and robustness for the revenue service. This paper presents the test results before the revenue service stared in June, 2013.

![Figure 10. The test track at the LTD maintenance yard](image)

Fig. 11 shows the lane keeping and precision docking performance based on twelve consecutive test runs (on Nov. 15, 2012) at the LTD yard track. As shown in Fig. 10, this yard track contains replicas of two docking curves on EmX, eastbound Agate and Walnut Stations, the two most difficult stations for docking maneuvers. The bus started the sharp docking curve (a two lane-width lane change with the smallest radii of +45m and -36m) at speeds above 32.4 km/h (9 m/s, 20 mph) and sometimes kept the speed at or above 32.4 km/h until it reached the simulated platform. The VAA controlled bus then drove along the platform (within 5cm), often at speed above 15 mph, and finally stopped straight (front and back ends) along the platform at marker number 115. The total travel distance along the platform was less than the full length of the articulate bus (18.3 m). The automated bus then maneuvered through a 90-degree sharp curve with a radius of 40 m and then immediately entered the eastbound Walnut Station docking curve. This docking curve is the sharpest among all the docking curves on the EmX route. The 60-ft (18m) articulate automated bus needed to complete a sharp lane change (with radii of +35m and -26m) and stop straight alongside the platform within two and a half length of the articulate bus. In addition, as shown in Fig 11, the bus speeds could reach 36 km/h (10 m/s, 22mph) in the middle of the lane change. Despite the variations in vehicle speeds, the bus’s lateral deviations remained very consistent from run to run, and the docking accuracy was better than 2 cm (i.e., STD < 1 cm) for both stations.

![Figure 11. Lane-keeping and docking performance in the yard](image)

Fig. 12 shows the lane keeping (and precision docking) performance based on twelve consecutive test runs (on April, 2013) on the EmX route in the westbound direction. As shown in the top plot, larger tracking errors (~20 cm) occurred at sharp curves (mostly docking curves) and the tracking errors were smaller than 10 cm at the straighter sections. The second plot illustrates that the steering wheel exceeded 50 degrees 16 times (the steering angle reached above 230 degrees at the E11 intersection turn). The bottom plot shows the large speed variations in this narrow corridor (the speed exceeded 64 km/h (40 mph) several times). The small radii, the large variations of speed, and the narrow lane all contributed to the difficulty of automatic control. The resultant STD of the tracking error, excluding the docking entry and exit curves, was 7.9 cm.

Fig. 13 displays the lane-keeping performance based on twelve consecutive test runs on the same day on the EmX route in the eastbound direction. Similar to that for the westbound direction, the larger tracking errors (~20 cm) occurred at sharp curves; the steering angle exceeded 50 degree 17 times (5 times above 150 degrees). In addition, the speed exceeded 40 mph a couple times during the testing. The resultant STD of the tracking error, excluding the docking entry and exit curves, was 7.2 cm.

Figs. 12, 13 and 14 illustrate that the docking accuracies for all those stations were within 2cm to the desired lateral positions (STD < 1 cm) for either the very sharp (25-35m radius) or the relatively mild (~100m radius) docking curves. For these twelve test runs, the maximum recorded speeds from starting the docking entry curve to when the bus front tire reached the platform (at the end of the curve) were: Walnut Station WB: 56 to 27 km/h, EB: 30 to 19 km/h;
Agate Station WB: 50 to 40 km/h, EB: 42 to 24 km/h; and Dad’s Gate Station WB: 48 to 27 km/h, EB: 40 to 27 km/h.

The robustness and performance of the steering controller was put to test when the bus was maneuvering through the sharp curves at high speeds while maintaining the accuracy along the station platform. No part of the bus (including tire) had ever made contact with the platform, station, or the curb.

VI. CONCLUSION

Research in automated steering control has been advanced for many years; however, practical applications requiring high accuracy and robustness still remain challenging. On the other hand, most human drivers perform the daily steering tasks with ease and without much training. Analyses of the DLC data revealed that drivers use a relatively straightforward “target and control scheme” to conduct the steering function. That is, drivers select preview targets and use a linear steering rate control based on the perceived vehicle angle errors with respect to the preview targets. Further synthesis of the T&C driver model shows that drivers effectively apply an implicit PID control that has certain invariant properties that make it robust against vehicle uncertainties and speed variations. By transforming this simple T&C scheme to a controller for the magnetic-sensor-based look-down lateral sensing system, a robust and high-performance steering controller was designed and implemented on a 60-ft articulated bus for operation on a narrow and curvy bus BRT route at Eugene, Oregon. The resultant system achieved lane-keeping and precision docking performance required for carrying passengers, and the revenue service started in June, 2013. The data from the revenue service will be analyzed and presented in the future.

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