Abstract—This paper has been focused on the design of throttle and brake controller for vehicle speed control. The control goals of the speed control are reduction of the effects of model uncertainty and external disturbance caused by the nonlinearity of the servo-level dynamics and the unpredictable driving resistance such as inclination of road and aerodynamic drag force. The tracking performance also should be guaranteed. To that end, a model free approach has been proposed in this paper. The proposed controller uses modified linear longitudinal vehicle model with reasonable assumptions to derive throttle and brake control law and a few parameters in the vehicle model has been defined to represent the system delay and variation of the vehicle parameters during driving. Since the defined parameters named vehicle characteristic variables (VCVs) vary depending on the vehicle states, an adaptation algorithm has been developed to estimate the VCVs. The error dynamics of the vehicle acceleration and VCVs have been analyzed to prove the stability of the proposed algorithm. The tracking performance of the model free cruise controller has been verified by simulation. The results not only show good tracking performance but also verify that the MFCC considerably reduces the effects of model uncertainty and external disturbance using adaptation algorithm.

I. INTRODUCTION

Automatic vehicle speed control or cruise control is one of the widely researched topics throughout the automotive industry. The goal of the speed automation is to improve the safety of highway traffic using automatic cruise control to replace human driver as well as make the traffic flow more efficient. First step of the speed automation is the cruise control (CC) which manipulates throttle angle to track the user-preset velocity. Then adaptive cruise control system (ACC) has been developed and marketed as an extension of the CC. The ACC allows the variation of the velocity of the subject vehicle depending on the behavior of the vehicle in front. While the conventional ACC only considers the higher speed range usually more than 30km/h, many researches taking into account stop-and-go scenarios have been reported in recent years.

A two-level structure is commonly used for ACC design. The upper level controller determines the desired velocity or desired acceleration based on the relative distance and velocity between the vehicle in front and the ACC equipped vehicle. The major issue of this level is to match the velocity and acceleration of the preceding vehicle as well as keep the safe distance. Most of researched in the literature integrates the concepts of range policy, string stability and human comfort to satisfy those objectives [1]-[7]. While the criteria of the upper level controller widely researched, the reports about the lower level controller are relatively rare. The studies are mainly focused on reducing the model uncertainty and external disturbance, since the vehicle dynamics are highly nonlinear and uncertain. Goodrich, M.A. has been proposed human centered design method to determine the throttle and brake actuation [8]. Some approaches have tried to develop model based lower level controller which determines control inputs using the vehicle parameters and inverse dynamics [9]-[11]. Instead of that, P. Shakouri used linearized vehicle model to design gain scheduling linear quadratic controller for throttle and brake actuation [12]. However, most of these approaches rely on accurate vehicle model. Thereby any parameter deviation could cause a loss of performance, or even to an unstable behavior. To tackle these problems, a fuzzy approach and neural network also have been demonstrated to compensate for neglected dynamics in vehicle model [13]-[17].

A model free cruise control technique has been proposed in this paper to reduce the effects of model uncertainty and external disturbance and to improve the tracking performance. The proposed controller computes throttle and brake input to track the desired acceleration command provided from the upper level controller. It has been designed based on a modified linear longitudinal vehicle model and few parameters in the vehicle model have been defined to represent control delay and lumped gain between the control inputs and vehicle acceleration. Then, the lumped gain, named vehicle characteristic variables (VCVs) since it vary during driving depending on the vehicle states, has been estimated using an adaptation algorithm. The error dynamics of the vehicle acceleration and VCVs have been analyzed to verify the stability of the proposed algorithm.

The performance of the MFCC has been compared with that of the conventional model based cruise controller through simulations. Two controller use the same upper level controller and preceding vehicle velocity profile which is obtained in real driving situations. In the simulations although any of vehicle parameters has not been used in the MFCC, it shows more elaborated performance than that of the model based controller.

The remainder of the paper is organized as follows. A modified longitudinal vehicle model has been derived for
controller design purpose in chapter 2. The MFCC has been briefly detailed in chapter 3. In chapter 4, the performance of the MFCC has been verified using simulations. Finally, conclusions are presented in chapter 5.

II. LONGITUDINAL VEHICLE MODEL

A modified longitudinal vehicle model has been derived from the complete longitudinal vehicle model in fig. 1 in order to obtain control law. The vehicle model has been developed with reasonable assumptions that no slip occurs at the tire road interface and power train from engine to wheel when a vehicle is under gradual maneuvers [13]. A force balance equation along the vehicle longitudinal axis gives:

\[ m \dot{v} = - \tau_v + R_s + mg \sin \theta \]  

(1)

where \( m \) is the mass of the vehicle, \( v \) is the longitudinal velocity and \( F_v \) is sum of front and rear tire forces, respectively. \( F_a \) is the longitudinal aero dynamic drag force, \( R_s \) is sum of rolling resistances of four wheels and \( \theta \) is the road grade. With the assumptions of no slip condition, the longitudinal tire force can be expressed as sum of engine torque and brake torque as follows:

\[ F_v = \frac{1}{R_g R_{eff}} T_e - \frac{1}{R_{eff}} T_b \]  

(2)

where \( R_g \) is total gear ratio of transmission and final reduction gear, \( R_{eff} \) is the effective tire radius, \( T_e \) is the engine torque and \( T_b \) is the brake torque. This paper assumes that there is locally a linear relation between the engine torque and throttle angle \( \theta \), and brake torque delay \( \tau_{th} \) with a throttle control delay of \( \tau_{th} \):

\[ T_e = k_{th} \theta \]  

(3)

In this model, the engine torque is proportional to the throttle angle through gain \( k_{th} \), which varies depending on the engine states. Likewise the engine torque, the relation between brake torque and brake pedal position \( \theta \) can be expressed as:

\[ T_b = k_b \theta \]  

(4)

where \( \tau_b \) is the brake control delay and \( k_b \) is a proportional gain for brake which is also vary depending on the vehicle states. During driving, the throttle and brake generally are applied independently. Therefore, according to which control inputs have been applied, the following vehicle dynamic model can be derived by combining eq. (1), (2), (3) and (4).

\[ \begin{align*}
\dot{F}_{th} &= (-G + \rho_{th} u_{th}) \text{ if } u_{th} \geq 0 \\
\dot{F}_{br} &= (-G + \rho_{br} u_b) \text{ if } u_b > 0 \\
\rho_{th} &= \frac{k_e}{m R_g R_{eff}}, \rho_{br} = \frac{k_b}{m R_{eff}}, G = \frac{F_a + R_s + mg \sin \theta}{m}
\end{align*} \]  

(5)

In this vehicle model, most of vehicle parameters of vehicle mass, aero dynamic drag force and rolling resistance could vary depending on the vehicle states such as vehicle speed, engine speed and gear ratio, etc. Besides, the assumption of linear relation between the engine/brake torque and control inputs includes model uncertainties caused by the nonlinearity of servo level dynamics. Therefore, the control variables of \( \rho \), \( \rho_{th} \), \( \rho_b \), named vehicle characteristic variables (VCVs) should be estimated during driving using a proper adaptation algorithm. The VCVs adaptation algorithm which is the major contribution of this paper will be detailed in chapter 3.

III. MODEL FREE CRUISE CONTROLLER

A model free cruise control technique has been detailed in this chapter. The controller is based on the modified longitudinal vehicle model introduced in previous chapter. The vehicle model has been derived from the longitudinal force balance equation with assumptions of linear relation between control input and tire force under no-slip condition. Using the vehicle model, control law for throttle and brake has been developed for the acceleration error to converge to zero. Undetermined variables named vehicle characteristic variables (VCVs) in the control law have been estimated using an adaptation algorithm. The schematic diagram of the MFCC is depicted in fig. 2.

![Figure 1. Longitudinal vehicle model](image1)

![Figure 2. Model free cruise controller](image2)
A. Throttle control law

Using the longitudinal vehicle model in eq. (5), throttle control law can be derived. If (5) is inverted and the vehicle acceleration is replaced with the desired acceleration \(a_{des}\), the control law can be obtained as follows:

\[
u_{th} = \frac{1}{\hat{\rho}_{th}} (a_{des} + \tau_{th} \dot{\rho}_{th} + \ldots)
\]

(6)

where \(\hat{\rho}_{th}\) is the estimated VCV for throttle and \(G_0\) is a nominal zero-throttling acceleration caused by the driving resistance \(G\) in eq. (5). In this control law, following remarks should be described:

Remark 1. If \(\hat{\rho}_{th} = \rho_{th}\) and \(G_0 = G\), the control law leads to following acceleration error dynamics

\[
\tau_{th} (\tau_{th} a_{des} + \ldots) = 0.
\]

(7)

Therefore the acceleration error will converge exponentially zero.

Remark 2. The vehicle characteristic variable is the most important factor in the throttle control law. This variable implies powertrain parameters from the engine to the wheel; therefore, it will be estimated using a proper adaptation algorithm.

Remark 3. The time constant represents the control delay through throttle and vehicle acceleration. It could vary depending on the vehicle states, but it is assumed as a constant of 0.2sec in this work.

Remark 4. If there is no throttle input, the vehicle decelerates according to the resistance forces such as rolling resistance, aero dynamic drag force and road grade. To achieve accurate control, the estimation of driving resistance is important. But, since these dynamics are unpredictable, this is no small task. However, heuristically, driving resistance is proportional to the vehicle longitudinal velocity. Additionally, if the adaptation algorithm properly designed, the effects of the driving resistance error can be relieved. Thus, \(G_0\) is defined as follows:

\[
G_0 = k_1 v + k_2
\]

(8)

where \(k_1\) and \(k_2\) are constants. These values are set such that \(G_0\) equals to 1m/s2 when the velocity is 30m/s.

B. Brake control law

The brake controller can be designed in the same manner to the throttle control law.

\[
u_{b} = \frac{1}{\hat{\rho}_{b}} (a_{des} + \tau_{b} \dot{\rho}_{b} + \ldots)
\]

(9)

where \(\hat{\rho}_{b}\) is the estimated vehicle characteristic variable for brake. Generally, the system response of brake is faster than that of throttle. Therefore, the time constant for brake has been set to 0.1sec.

C. VCVs adaptation algorithm

In the vehicle model in (5), the VCVs imply the vehicle power train and brake system parameters which are influenced by the vehicle states. Thus they vary during driving. Therefore, the VCVs should be estimated in order to control vehicle longitudinal motion accurately. The VCVs adaptation algorithm begins with the error dynamics analysis. The acceleration error and VCVs error has been defined as follows:

\[
e_1 = a_{des} - a
\]

(10)

Then the error dynamics when the throttle is activated can be defined as follows:

\[
\tau_{th} (\tau_{th} a_{des} + \ldots) = \rho_{th} - \hat{\rho}_{th}
\]

(11)

The adaptation algorithm should compensate the acceleration error during driving. Therefore, the following adaptation algorithm has been proposed:

\[
\dot{\rho}_{th} = \frac{1}{u_{th}} (a_{des} - a)
\]

(12)

where \(\gamma_{th}\) is the adaptation gain for throttle. Finally combining eq.(13), (18) and (19), the following error dynamics can be obtained:

\[
\tau_{th} (\tau_{th} a_{des} + \ldots) = \frac{\rho_{th} - \hat{\rho}_{th}}{u_{th}} + \frac{\gamma_{th}}{u_{th}}
\]

(13)

Therefore the poles of the proposed controller can be easily manipulated by adjusting the adaptation gain \(\gamma_{th}\). In other word, tracking performance is only influenced by the time constant of power train and adaptation gain, not the complicate vehicle parameters. Thus, the controller can be easily implemented various type of vehicle even if the target vehicle parameters were unknown. It also implies that the proposed controller is robust to the parameter deviation during the life time of the vehicle and external disturbance. Secondly, the switching algorithm can be obtained from the error dynamics. Since the control inputs is included in the denominator of the adaptation algorithm, the control action...
and the adaptation algorithm should be initiated when the calculated control input in eq. (6) and (9) are greater than a small value $\varepsilon$. Therefore, the switching condition has been determined as follows:

\[
\begin{align*}
    &\text{if } a_{des} + \tau_{ah} \cdot \omega - \omega \cdot \varepsilon \cdot u_{h} = 0 \\
    &\text{elseif } a_{des} + \tau_{bh} \cdot \omega - \omega \cdot \varepsilon \cdot u_{b} = 0 \\
    &\text{else } u_{ah} = u_{bh} = 0
\end{align*}
\]

(15)

The same error dynamics and characteristic equation can be obtained for the brake control using the same formulation of the control law and adaptation algorithm, but the adaptation gain should be tuned differently because the system response of the brake is generally faster than that of the throttle.

The proposed controller is longitudinal velocity controller which determines the throttle and brake control inputs to follow the desired acceleration command. The controller determines control inputs using only the desired acceleration and measured acceleration, not the vehicle parameters by introducing the vehicle characteristic variables and the adaptation algorithm. Since the adaptation algorithm manipulate control input based on the acceleration errors, the acceleration error could be compensated without information about the vehicle parameters. Moreover, the proposed controller could robust to the model uncertainty and external disturbance because of the adaptation algorithm.

IV. SIMULATION RESULTS

A. Comparison with model based adaptive cruise controller

The performance of model free cruise controller has been convicted by comparing it with that of conventional model based adaptive cruise controller. The same preceding vehicle velocity profile of normal driving condition has been applied to both controllers and the same upper level controller has been used to generate desired acceleration command. The controller uses optimal control technique to determine the desired acceleration and the control gains for the velocity error and inter distance error in the optimal controller are constrained depending on the velocity of subject vehicle in order to guarantee safety and comfort criterion [9].

\[
a_{des} = -k_{1} (\omega_{des} - \omega) - k_{2}v_{rel}
\]

(16)

where $k_{1}$ and $k_{2}$ are proportional gain for clearance error and relative velocity, respectively. $\omega_{des}$ is the desired inter distance which is proportional to the velocity of subject vehicle, $\omega$ is the measured inter distance and $v_{rel}$ is the relative velocity.

The target vehicle is a medium passenger car and the vehicle parameters for the lower level controller of conventional ACC have been obtained from the experimental data and applied to the simulation. The lower level controller of the ACC is based on the inverse dynamics to calculate desired throttle angle and brake pressure [8]. The algorithm determines the required net torque from the desired acceleration. Then, the torque converter map and engine map is incorporated to calculate the throttle angle. A steady state lumped gain has been used to determine the desired brake pressure. A PID compensation for the acceleration error has been used to compensate acceleration error, external disturbance and model uncertainty. The switching between the throttle and brake has been determined based on the switching line which is obtained from zero throttling acceleration data with switching margin. On the contrary, in MFCC, the time constant of throttle control law is set to 0.2sec for throttle and 0.1sec for brake. The adaptation gain has been chosen for the damping ratio of the characteristic equation in (14) to be 1.0. The simulation results of velocities, accelerations, control inputs and VCVs have been depicted in fig. 3.
B. Comparison with model based adaptive cruise controller under external disturbance

Major advantage of the model free cruise controller is represented in this section. Since the adaptation algorithm compensates acceleration error by observing the measured acceleration signal, the proposed algorithm could robust to the external disturbance and model uncertainty. To verify that, a random road grade as external disturbance in fig. 4 has been applied to both controllers with the same preceding vehicle velocity profile to the previous simulation. The simulation results depicted in fig. 5 show that the MFCC is more robust to the external disturbance than the conventional ACC. While the acceleration error of conventional ACC increases because of the gravitational force during driving, the MFCC shows more elaborated tracking performance. Since the adaptation algorithm automatically manipulate the VCVs to compensate the acceleration error as depicted in the comparison results in fig. 5, robust acceleration tracking has been achieved. The VCVs converges to higher value when the vehicle is going downhill in order to decrease throttle inputs. On the contrary to this, when the vehicle is going uphill the VCVs converges to lower value to increase throttle inputs. Therefore the model free cruise controller can be robust to the external disturbance. This compensation process also could allow the MFCC to robust to the model uncertainty because the generated acceleration error by model uncertainty could be compensated using the adaptation algorithm. That is the reason the MFCC could be applied to a default vehicle even if the vehicle parameter were unknown.

V. CONCLUSION

A model free cruise control technique has been proposed as a solution of vehicle longitudinal control problem. The MFCC uses the modified longitudinal vehicle model with reasonable assumptions and compensates acceleration error using the adaptation algorithm. Simulation results show that excellent performance of the MFCC under the model uncertainty and external disturbance. These results indicate that the MFCC is a highly recommended solution for the speed control of a test vehicle since the tracking performance is close to that of conventional ACC as well as it can be implemented to the vehicle whose power train and brake system parameters are unknown. Moreover, since there is only one control parameter of the adaptation gain, the proposed controller can be easily implemented to a target vehicle without parameter investigation process. Additionally, the MFCC is robust to the
model uncertainty and external disturbance. These properties would be great advantages to control the vehicle longitudinal motion.

![Graph](image)

Figure 5. Comparison ACC and MFCC under normal driving condition with external disturbance

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