The Impact of Predictive Cruise Control on Traffic Flow and Energy Consumption

Sehyun Tak¹ and Hwasoo Yeo²

¹Smart Transportation System Laboratory, Department of Civil and environmental Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea PH (042) 350-3674; email: taksehyun@kaist.ac.kr
²Smart Transportation System Laboratory, Department of Civil and environmental Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea PH (042) 350-3634; email: hwasoo@kaist.edu

ABSTRACT

A vehicle Predictive Cruise Control system has been developed to improve the fuel efficiency of vehicle and traffic flow performance based on the asymmetric traffic theory. The Predictive Cruise Control system consists of four parts: (1) Deceleration based Safety Surrogate Measure, (2) Adaptive Cruise Control, (3) Multi-vehicle measurement, and (4) Predictive Cruise Control. Adaptive Cruise Control basically decides the acceleration/deceleration action based on the estimated deceleration-based safety surrogate measure of the first leader vehicle. Then, Predictive Cruise Control adjusts the acceleration/deceleration action based on the multi-vehicle measurements, which represent the future traffic condition of the subject vehicle. The developed system is tested by simulating the real vehicle trajectories from the NGSIM data and comparing the results with real following pattern. It was found that the newly proposed Predictive Cruise Control system can contribute to energy consumption and traffic flow performance, because it can effectively suppress the shockwave from the downstream and remove the unnecessary deceleration and acceleration action.

Introduction

It is known that many vehicle accidents are due to the carelessness, and human error. Therefore, many efforts have been made to improve safety by limiting a vehicle’s maximum speed, ensuring the safe distance, and pre-alert system. Accident rate has been reduced because of these efforts. However, in recent years, accident reduction rate is at a standstill. And, an innovative system is needed to improve the human’s safety in vehicle operations. The other issues related to the human driving behavior are traffic flow stability and energy consumption. Overreactions of drivers on the change in the leader vehicle propagate unnecessary shockwave and also make
negative impact on traffic flow and fuel consumption (Davis, 2004). So, reducing the impact of shockwave is important to improve the traffic flow stability.

One of the strong alternatives to solve these problems is Adaptive Cruise Control (ACC). Adaptive cruise control system enhances regular cruise control by automatically changing the velocity and spacing (Zhou and Peng, 2005). ACC vehicle is controlled based on the information, such as velocity of preceding vehicle and space between two vehicles. Such information is gathered from in-vehicle devices, communications with adjacent vehicles, and transportation infrastructure. In general, for ACC system, there are two types of spacing policies: constant space headway (or time headway) policy and variable space headway policy. Constant space headway policy determines the distance between preceding vehicle and following vehicle based on the assumption that two inter-vehicle distance and velocity have a linear relationship. This policy is almost entirely focusing on the velocity and space headway at a certain time. So, headway is linearly increased as the speed increases. Variable space headway policy considers not only the speed and spacing but also the situation faced by a certain vehicle, such as reduction of the relative velocity, increase in the relative velocity, and temporary shock wave. So, variable space headway policy-based vehicle has different space headway depending on the situation, even though space and velocity remains the same.

Out of the two types of space headway policies, the constant space headway policy (or time headway policy) is the one that is frequently used in ACC designs (Ioannou and Chien, 1993, Ioannou and Stefanovic, 2005, Darbha and Rajagopal, 1999). Constant space headway-based ACC vehicle has a capability to improve driver safety and increase the road capacity. However, Constant space headway policy has some disadvantages. First, constant space headway policy-based ACC vehicle uses more fuel, because it responds too sensitively to the changes in the preceding vehicle. Second, constant space headway policy-based ACC vehicle cannot mitigate the shock wave even though it can prevent the propagation of shockwave. So, to overcome these shortcomings, we develop the new Predictive Cruise Control (PCC) and evaluate the potential effects of the PCC on traffic stability and energy consumption.

**Predictive Cruise Control Strategy**

The newly proposed Predictive Cruise Control (PCC) consists of four parts: (1) Deceleration based safety surrogate measure, (2) Adaptive cruise control, (3) Multi-vehicle measure, and (4) Predictive Cruise Control as shown in Figure 1. Adaptive Cruise Control system provides the automatic tracking of the first leader vehicle. The optimal acceleration action and attenuation of preceding traffic is indicated as PCC based on the multi-vehicle measure, which indicates the situation of the preceding vehicles. The proposed PCC differs from ACC in that predicts the near future of the subject vehicle by utilizing the multi-vehicle measure. Detailed strategies are described as follows.

1. Development of new safety surrogate measure for single vehicle.
The selection and design of the measure, such as spacing policy for determining the action for acceleration, deceleration, and constant speed, are considered as the prior factors in ACC (Swaroop and Rajagopal, 2001). ACC determines the collision risk of the subject vehicle based on the measure or spacing policy. In order to increase the efficiency and reliability of ACC system, various measures such as time headway, space headway, safety factor spacing, time to collision, and nonlinear spacing policy have been developed. However, the current measures for ACC have some limitations to reflect the characteristics of individual drivers and vehicle such as maximum braking performance, preferred acceleration rate, and etc. These limitations may cause uncomfortable environment for the driver due to the mechanical motion of the vehicle.

Figure 1. Overview of the components of the proposed Predictive Cruise Control

To enhance the current ACC, we propose a new measure, Deceleration-based Safety Surrogate Measure (DSSM), which is based on the safety condition (Yeo and Skabardonis, Yeo, 2008, Yeo et al., 2011). Traffic safety is one of the most important issues to motivate researches into ACC and collision warning or prevention technology is the essential function in ACC system. Thus, to meet the safety requirements, we develop the new measure based on the concept of safety surrogate measure, which is the widely used safety performance indicator. Deceleration-based Safety Surrogate Measure (DSSM) can be expressed as the function of the information obtained from V2V communication technology. To represent the collision risk based on the vehicle performance, the DSSM for ACC is defined as the function of braking performance as follows.

\[
K = \left( x_n(t)-x_{n+1}(t) \right) \left[ 2+ v_n(t)+a_n(t) \cdot \tau \right]^2 \cdot \left( v_{n+1}(t)/2+ \frac{b_{n+1}(t)+b_{\text{max},n+1}}{4} \right) \left( \frac{b_{n+1}(t)-b_{\text{max},n+1}}{x_{n+1}} \right) + \left( v_n(t)/2+a_n(t) \cdot \tau \right) \cdot \left( \frac{\dot{a}_n(t)+b_{\text{max},n} \cdot \frac{\dot{a}_n(t)+b_{\text{max},n}}{2} + b_{\text{max},n}}{2} \right) \]  

\[
b_n(t) = b_{\text{max},n+1}(t) \left( \frac{\dot{a}_n(t)+b_{\text{max},n+1}(t)}{2} \right) \]  

\[
\text{DSSM} = \frac{b_n(t)}{b_{\text{max},n}} \]  

where \( a_n(t) \) is the acceleration rate of following vehicle at time \( t \), \( a_{n+1}(t) \) is the acceleration rate of leader vehicle at time \( t \), \( b_{\text{max},n+1} \) is the maximum braking rate of leader vehicle, which represents the vehicle’s mechanical deceleration performance,
\( b_{n}(t) \) is the needed deceleration rate of following vehicle to avoid the accident at time \( t \), \( b_{\text{max},n} \) is the maximum braking rate of following vehicle, \( v_{n-1}(t) \) is the speed of leader vehicle at time \( t \), \( v_{n}(t) \) is the speed of following vehicle at time \( t \), \( L_{n-1} \) is the maximum variation of acceleration of leader vehicle, \( \Delta a \) is the maximum variation of acceleration of following vehicle, \( v_{n}(t+\tau) \) is the expected speed of following vehicle after \( \tau \), \( x_{n-1}(t) \) is the location of leader vehicle at time \( t \), \( x_{n}(t) \) is the location of following vehicle at time \( t \), \( \tau \) is the perception reaction time, and \( s_{n-1} \) is the length of leader vehicle.

ACC system always works with a human driver. Therefore, the first step in designing a vehicle control strategy for the application of ACC system is to develop the measure based on the driving behavior characteristics. The DSSM reflects the collision risk between two consecutive vehicles based on human and machine characteristics. The driver’s comfort can be increased by using a preferred acceleration rate as the individual vehicle’s \( a_{\text{pre}}(t) \) value, preferred braking rate as the individual vehicle’s \( b_{\text{max},n} \) value, and preferred variation of acceleration rate as the individual vehicle’s \( \Delta a \) value.

(2) Development of control algorithm for single vehicle.

The DSSM value represents the collision risk of the subject vehicle. The DSSM value larger than one represents that the subject vehicle cannot avoid the accident when leader reduce the speed with its maximum braking rate. The DSSM value greater than or equal to 1.2 means that the following vehicle cannot physically avoid collision when the leading vehicle stops with full deceleration. In reality, the drivers’ patterns show that most of drivers conduct severe deceleration when DSSM value is greater than or equal to 1.2. DSSM value of 0.85 can be considered as the slightly dangerous situation and the driver shows the average number of approximately 0.85. By referring these values, the control algorithm is developed as shown in Figure 2.

![Figure 2. Longitudinal control algorithm of Adaptive Cruise Control (ACC) for single vehicle](image-url)

Figure 2 shows the longitudinal control algorithm of ACC for single vehicle. The acceleration and deceleration rate is determined based on the calculated DSSM value. The longitudinal control algorithm consists of three parts. (1) The subject vehicle increases the speed proportional to the difference between \( \text{Std}_{\text{up}} \) and calculated DSSM. \( \text{Std}_{\text{up}} \) is the reference point for determining the acceleration action and 0.7 is
used for that value in this study. The frequent acceleration action is prevented and the intensity of acceleration rate is increased by decreasing the Std\textsubscript{up}. (2) The subject vehicle maintains the current speed when calculated DSSM is between Std\textsubscript{up} and Std\textsubscript{do}. (3) The subject vehicle reduces the speed proportional to the difference between Std\textsubscript{do} and calculated DSSM. Std\textsubscript{do} is the reference point for determining the deceleration action and 0.85 is used for that value in this study. By changing the Std\textsubscript{do} value, the degree of risk taking is determined. For example, the driver who wants to reduce the collision risk can decrease the Std\textsubscript{do}. On the other hand, the driver who does not want frequent braking can increase the Std\textsubscript{do} up to 1.0. Std\textsubscript{up} and Std\textsubscript{do} can be changed depending on the user preferences and system objectives.

(3) Development of algorithm on traffic condition.

To predict the future traffic condition, the proposed control algorithm uses the platoon concept and a multi-vehicle measure. The measure of the preceding vehicles can represent the future state of the subject vehicle. For example, the speed reduction of the foremost vehicle in a platoon means that the subject vehicle would reduce its speed in near future. In the situation based on the concept of DSSM, an increase in foremost DSSM, which is the DSSM\textsubscript{lead05} in Figure 1, has the possibility of increasing the subject vehicle’s DSSM, which is the DSSM\textsubscript{fol} in Figure 1, even though the DSSM\textsubscript{lead01} is low. Conversely, low level of foremost DSSM leads the subject vehicle to low level of DSSM even though DSSM\textsubscript{lead01} is high. To indicate the future impact of the preceding vehicles on the subject vehicle, multi-vehicle DSSM is defined as:

\[
DSSM_{co} = \sum_{i=1}^{5} D_i \cdot W_i
\]

where DSSM\textsubscript{co} is the multi-vehicle DSSM, \(D_i\) is the DSSM of the \(i\)-th vehicle, and \(W_i\) is the weighting factor of the \(i\)-th vehicle.

\(D_i\) is also calculated by using equation (1), (2), and (3). \(W_i\) can be adjusted depending on the purpose of the user. If a user wants to response to \(D_i\) more sensitively, which is the nearest future for the subject vehicle, the user can increase the \(W_i\). If the user wants to response to the further future, the user can increase the \(W_5\). In the next chapter, in order to evaluate the performance of the proposed PCC method we assigned 0.5 for \(W_1\), 0.3 for \(W_2\), 0.1 for \(W_3\), 0.075 for \(W_4\), and 0.025 for \(W_5\).

(4) Development of Predictive cruise control

Figure 3 shows the PCC algorithm by using DSSM\textsubscript{co} and DSSM\textsubscript{fol}. As shown in Figure 3, the control space is divided into 10 regions, where each region corresponds to the control mode of ACC for subject vehicle. The PCC system compares the measurements of DSSM\textsubscript{fol} and DSSSM\textsubscript{co} to the diagram to select the control mode. DSSM\textsubscript{fol} represents the DSSM value of the subject vehicle, and DSSM\textsubscript{co} represents the weighted average of DSSM for preceding vehicles. Region (1), (5), and (10) represent the no change mode of PCC. No change means that subject vehicle determines the deceleration/acceleration rate with the same level of single vehicle mode, so called ACC mode. Region (6), (8), and (9) means that DSSM of subject
vehicle will be reduced in the near future. So, subject vehicle accelerates more than the calculated acceleration rate in ACC mode by increasing the Std_{do} value. In region (2), (3), and (4), subject vehicle reduces the acceleration rate less than ACC mode by reducing the Std_{up}. In this region, subject vehicle increases the speed when only considering the nearest leader vehicle. However, the subject vehicle reduces the acceleration rate, because high DSSM of preceding vehicle may lead to deceleration traffic condition. Region (7) represents the more deceleration mode of PCC. In this mode, subject vehicle decelerates more than the calculated rate in ACC mode by reducing the Std_{do}.

In the PCC system, there is a possibility that collision risk can be underestimated compared to ACC system, because the safety of a certain vehicle is only related to its immediate leading vehicle. For example, let us consider the case when the four leading vehicles are proceeding with high speed and only the immediate leading vehicle suddenly stops for some reason. In this case, since the PCC uses a weighted average DSSM value of the multiple leading vehicles, it may suggest less deceleration than ACC. In order to overcome this limitation, we have decided that a single vehicle’s Std_{do} should be smaller than 1.0 and that the full deceleration should be made at 1.2 of a single vehicle’s DSSM value.

![Figure 3. DSSM_{fd} versus DSSM_{cu} diagram](image)

**Evaluation of the Predictive Cruise Control**

To evaluate the proposed control algorithm, we simulate the proposed ACC and PCC algorithms. All cases include one or more sections that experience shockwave. For the simulation, we used the Next Generation Simulation (NGSIM) trajectory data collected from a highway site called I-80 in California, US (2006). The effectiveness of proposed ACC for single vehicle and PCC can be evaluated by verifying whether the control algorithm is able to attenuate the shockwave and reduce the energy...
consumption during acceleration. As shown in Figure 4, both ACC equipped vehicle and PCC equipped vehicle show a stable trajectory than human driver. Especially, PCC shows the best capabilities that can attenuate the shockwave because the proposed PCC can predict the shockwave in advance based on the information of the preceding vehicle. As shown in Figure 4, PCC makes a smooth trajectory by reducing the acceleration rate before meeting shockwave. Conversely, PCC also makes a smooth trajectory by reducing the deceleration rate or accelerating before leaving the influential area of shockwave. This smooth trajectory reduces the negative effects of shockwaves.

![Figure 4](image.png)

**Figure 4. The trajectory of the human driver, ACC equipped vehicle and PCC equipped vehicle.**

There are several ways to estimate the energy efficiency. In this paper, the energy efficiency of the each mode is estimated based on the acceleration amount. The acceleration amount is the sum of each time step’s acceleration value. As shown in Table 1, PCC generally shows the best energy efficiency, and ACC shows the second higher energy efficiency. Compared to other modes, PCC can effectively remove the unnecessary deceleration and acceleration behaviors by predicting the future traffic condition. For example, PCC reduces the acceleration rate or speed when shockwave is coming even though acceleration is recommended considering only the first leader vehicle. From the perspective of collision risk, DSSM of PCC generally shows the similar trend with DSSM of ACC, because PCC takes deceleration or acceleration action in advance to reduce the collision risk by predicting the future traffic condition.

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
<th>Case 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration amount</td>
<td>863</td>
<td>636</td>
<td>746</td>
<td>568</td>
<td>846</td>
<td>813</td>
<td>1099</td>
</tr>
<tr>
<td>Mean DSSM</td>
<td>0.82</td>
<td>0.66</td>
<td>0.78</td>
<td>0.77</td>
<td>0.47</td>
<td>0.51</td>
<td>0.48</td>
</tr>
<tr>
<td>ACC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration amount</td>
<td>519</td>
<td>523</td>
<td>427</td>
<td>552</td>
<td>708</td>
<td>635</td>
<td>742</td>
</tr>
<tr>
<td>Mean DSSM</td>
<td>0.67</td>
<td>0.72</td>
<td>0.73</td>
<td>0.72</td>
<td>0.77</td>
<td>0.78</td>
<td>0.76</td>
</tr>
<tr>
<td>PCC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration amount</td>
<td>470</td>
<td>498</td>
<td>502</td>
<td>461</td>
<td>607</td>
<td>551</td>
<td>604</td>
</tr>
<tr>
<td>Mean DSSM</td>
<td>0.68</td>
<td>0.73</td>
<td>0.75</td>
<td>0.73</td>
<td>0.70</td>
<td>0.77</td>
<td>0.73</td>
</tr>
</tbody>
</table>

**Table 1. Acceleration and DSSM of human driver, ACC equipped vehicle and PCC equipped vehicle.**

**Conclusions and Future work**

This paper proposed and analyzed the design of the new Predictive Cruise Control (PCC) systems from the point of view of improving traffic flow stability and
safety performance while reducing the energy consumption of the vehicle. The new measure called Deceleration based Safety Surrogate Measure (DSSM) was developed and applied to the Predictive Cruise Control (PCC). Practical advantages of the PCC were simulated and compared to human driver. The results show that PCC mode can significantly improve the energy efficiency while maintaining the similar collision risk (DSSM).

In order to implement PCC system successfully, other things also have to be considered for further development of the proposed PCC. The proposed PCC model has focused only on the individual vehicles’ car-following behaviors. It is suggested to perform further studies considering various situations like lane-changing events. Furthermore, this study is performed under the assumption that the communication environment among vehicles is perfect. It is postulated that there is no error or delay during communication process. It is also suggested that further studies to consider communication related factors, such as error rate, computation time, and transmission speed.

Acknowledgment

This work is financially supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0011558).

Reference


