An Effect Evaluation of Automatic Driving Control for Passing through Intersections

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Abstract: This paper reports on effect evaluation, which focuses on intersections, as a part of a study to clarify the effects of automatic driving control. While intersections are essential for vehicle traffic, they cause several traffic problems such as accidents and congestion. Although many technologies have been developed to solve these problems, they remain imperfect. Recently, there have been many attempts to realize automatic driving control. Automatic driving control is expected to remove the uncertainty of manual driving and enhance safety and efficiency. Intersections are no exception: automatic driving technologies are expected to decrease traffic congestion and yield an energy-saving effect while reducing accidents at intersections. However, previous studies have not sufficiently clarified the magnitude attainable by these effects or what types of automatic driving technologies are needed to achieve them. This study therefore evaluates the effects on traffic flow of automatic driving control for passing through intersections. In this paper, first, the background surrounding automatic driving technologies is described to clarify the context of this study. Next, related works that have examined the effects of automatic driving control, such as automatic driving control for passing through intersections, are introduced. Then, vehicle behavior models designed for effect evaluation by simulation are explained. Finally, evaluation using the simulated vehicle behavior models is reported. The experimental evaluation verifies that automatic driving control for passing through intersections yields much greater effect in decreasing traffic congestion and energy saving than conventional traffic control using traffic signals.

Keywords: Automatic Driving System, Intelligent Transport Systems, Advanced Vehicle Control and Safety Systems, Intersection Traffic Management,

1. Introduction

Recent years have seen numerous advances in the field of vehicular driving control. Miniaturization and ongoing reductions in the price of semi-conductors have contributed to enhancing the performance of devices required for driving control, such as sensors, actuators, and electric control units (ECUs). Conventional driving control is accomplished by relying on drivers’ cooperation in terms of recognition, judgment, and operation. Lately, however, driving control, which can replace almost all driving tasks, has been studied and developed, and some manufacturers aim to accomplish fully autonomous driving around 2020.

Advanced driving control not only decreases drivers’ workloads, but also contributes to the efficiency of the whole traffic system. For example, communication and the use of sensors enable recognition using a wide range of high-resolution information. A high-performance computer accomplishes appropriate judgment with recognition information. In addition, a high-performance actuator enables operation at high speed and with high accuracy based on appropriate judgment. The implementation of these devices would accomplish a traffic system beyond the current system, which only consists of manual driving.

On the other hand, some people would prefer that advanced driving control does not spread. In general, vehicles are said to have higher palatability than other forms of transport. This is why drivers are concerned about a scenario in which their driving pleasure would be lost if advanced driving control were to prevail. These opinions cannot be ignored and they could disrupt attempts to accomplish advanced driving control.

One of the reasons for the above concerns is that the benefits derived from advanced driving control are not well understood. Although driving control fields have developed technologies for advanced driving control, the quantitative effect of these driving controls on society is not known. Thus, drivers cannot compare the driving pleasure they would forfeit by using driving control and the benefits they would derive from driving control. In addition, automated driving control has not been implemented reliably in the automotive market. In other words, we should proactively support the quantitative evaluation of the effect of advanced driving control to attempt to accomplish implementation of control.

This study therefore focuses on the evaluation of the energy-saving effect of advanced driving control systems.
on a traffic system. Specifically, this study evaluates the energy-saving effect on traffic systems by comparing automatic driving control for passing through intersections developed as part of this study with manual driving.

Section 2 introduces related work on energy-saving technologies of traffic systems and clarifies their technological issues. Details of the simulation models developed for the evaluation of the energy-saving effect on automatic driving control for passing through intersections are described in Section 3. Section 4 reports the conditions and results of the simulation evaluation of the energy-saving effect, and the paper is concluded in Section 5. Figure 1 shows the vehicles and the test site that were used for the experimental evaluation of the automatic driving control for passing through intersections.

2. Related Work

This section introduces related work on energy conservation in traffic systems.

Approaches to saving energy in traffic systems are largely classified into two categories: the influence on the infrastructure and that on the vehicles. Recent studies tend to assume that a wireless communication device is installed in each vehicle.

The main approach that is followed to achieve energy saving is designed to influence the infrastructure by way of controlling traffic signals. This has led to the development of an adaptive traffic signal control algorithm [1] based on a wireless Vehicular Ad-hoc NETwork (VANET), which was evaluated using actual traffic data in the city of Moncton.

On the other hand, methods that accomplish energy saving by influencing vehicles are largely classified into two groups: methods that offer information about traffic congestion or optimal routes and methods that use vehicle control. Collins and Muntean [2] proposed an optimal route calculation algorithm named TraffCon to offer information to connected vehicles, whereas Gupta and Younis [3] proposed a method to guide each vehicle along its optimal route by adaptively managing the traffic flow through communication with other vehicles. These two studies adopted methods to offer information regarding traffic congestion or optimal routing to drivers.

a) Driving control methods aimed at accomplishing energy saving can be classified into three groups: a) autonomous driving control specific to passing through intersections. Milanes et al. [4] proposed driving control for passing through intersections using vehicle-to-vehicle (V2V) communication and fuzzy controllers. Our previous work also involved the development of an automatic driving control system for passing through intersections and certified the technological validity of the system by conducting the evaluation using several small electric vehicles (EVs). The vehicle control on which this study focuses also belongs to this classification;

b) Driving control that simulates energy saving during manual driving. Some studies aim to achieve efficient driving by considering the factors that influence energy consumption, such as the road slope, preceding vehicles, and traffic signals. These studies are not introduced in this paper because they are beyond the scope of this study;

c) A V2V distance control system that targets the expansion of traffic capacity or the smoothening of traffic flow. A representative V2V distance control system targeting expansion of the traffic capacity is platoon control. Some large research projects on platoon control, such as CHAUFFEUR, SARTRE, KONVOI, OATH, and Energy ITS, are recently underway in countries around the world [5]–[8]. We also conducted studies focusing on the stability of platoon control and the transference sequence of the control [9] [10].

Thus, much related work attempting to improve energy saving of traffic systems has been conducted before. In these studies, autonomous driving control specific to passing through intersections is expected to accomplish a large energy-saving effect. Control models for autonomous driving control specifically for passing through intersections have already been proposed, even though no studies have shown that these controls are able to accomplish energy saving. Therefore, this study aims to use simulation to clarify the energy-saving effect of autonomous driving control specifically for passing through intersections.

3. Simulation Models

This section provides details of the driving behavior model for simulating the evaluation of energy saving. The design of the model is based on the automatic driving control system for passing through intersections, which we developed before. First, the design of a manual driving behavior model based on the Intelligent Driver Model (IDM), which is used for comparative evaluation purposes, is explained prior to describing the controlled vehicle behavior model of which the design is based on automatic driving control for passing through intersections.

3.1 Manual Vehicle Behavior Model

This model simulates the driving behavior of a typical driver with consideration for preceding vehicles and traffic signals, based
on IDM. IDM is one of the continuous time vehicle follow-
driver models, a well-known model used for traffic flow
simulations [11]. This study modified the IDM and added
the behavior of traffic signals in order to reproduce the man-
ual driving behavior of vehicles on city roads.

The IDM modified in this study consists of free road and
interaction terms as in the original IDM. First, the free road
terms simulates driving behavior in which the vehicle accel-
erates, aiming at a target velocity when there are no other
vehicles or traffic signals on the road. An equation for the
target acceleration of the free road term is below:

\[
\hat{v}_{t,b} = \frac{dv_{t,b}}{dt} = a \left[ 1 - \left( \frac{v}{v_0} \right)^\delta \right]
\]

where \(v\) is the vehicle’s velocity and \(v_0\) indicates the target
velocity of the vehicle fixed in advance. In addition, \(\delta\) is a
model parameter for the acceleration exponent and \(a\) is a
model parameter fixed to perform a driving behavior close to
that of the objective vehicle.

Next, the interaction term simulates behavior for the case
where other vehicles or traffic signals are ahead of the vehi-
cle and the vehicle drives according to their relative distance
or velocity. This model calculates the target acceleration of
the vehicle as below:

\[
\hat{v}_{t,f} = \frac{dv_{t,f}}{dt} = -a \left( \frac{s'(v, v_f)}{s_f} \right)^2
\]

\(s' = \begin{cases} 
0 + \max \left[ 0, vT + \frac{v}{2 \sqrt{ab}} \right] 
& \left( s_0 \leq s_f \text{ and signal is red} \right) \\
0 + \max \left[ 0, vT + \frac{v - v_f}{2 \sqrt{ab}} \right] 
& \left( \text{otherwise} \right)
\end{cases}
\]

where \(s_0\) is a parameter for minimum V2V distance. The
signal \(s_f\) indicates the V2V distance of the vehicle and the
nearest preceding vehicle in the same lane. In addition, \(v\) and
\(v_f\) are the velocity of the vehicle and of the nearest
preceding vehicle, respectively. In this model, \(s_0\) cannot be
smaller than \(s_f\) and \(s_f\) indicates the distance of the vehicle
and the nearest traffic signal ahead of the vehicle. If a tra-
fic signal is closer to the vehicle than the nearest preceding
vehicle and the traffic signal indicates a red light, the model
treats this situation in the same way as when a vehicle is
stopped at the position of the traffic signal. Finally, \(b\) is a
model parameter for comfortable braking deceleration.

3.2 Controlled Vehicle Behavior Model This model
simulates the automatic driving control method, which
we previously developed for passing through intersec-
tions. This work proposes two types of approaches: a control sys-

em type and VANET type. The control system type uses
a control center to control the arrival time and passing time
of vehicles passing through the intersection. This type also
ensures that vehicles pass through the intersection on time.
On the other hand, the VANET type shares the distance to
and velocity of each vehicle in relation to the intersection.
This type also controls each vehicle to form an artificial pla-
toon. Both types of automatic driving control for passing
through intersections have common points: they need no
traffic signals, adjust timing to pass through the intersection
by driving control before entering, and target the efficient
use of occupancy time of the vehicles in the intersection.

This study therefore shares the distance to the intersec-
tion and the current velocity of each vehicle before entering
the intersection similar to the VANET type and then repro-
duces driving behavior which simulates the artificial pla-
toon formed by each vehicle.

Specifically, as illustrated in Fig. 2(a), in an intersection
that consists of two one-way roads where right/left turns are
prohibited on both roads, a control activation point is pre-
pared at some distance before each entrance point of the
intersection. All the vehicles driving from the control ac-
tivation point to pass through the intersection can continu-
ously share information. In addition, vehicles that have
already passed each control activation point can form an art-
ificial platoon by duplicating the two roads artificially as il-
ustrated in Fig. 2(b), even for vehicles traveling according
to the “first in first out” scheme. If vehicles can maintain
a constant artificial V2V distance from the control activa-
tion point to the entrance of the intersection using platoon
control, these vehicles never cause collisions.

Therefore this study designed a controlled vehicle behav-
ior model using IDM and a platoon control algorithm as re-
ferences [11]. The controlled vehicle behavior model con-
stitutes of the free road term and the platooning term. The free
road term is the same as that in the manual vehicle behavior
model. The platooning term calculates the target acceler-
ation of the vehicle as in the equations below:

\[
\hat{v}_{t,f} = \frac{dv_{t,f}}{dt} = \begin{cases} 
\hat{v}_{s,t,f} = K_d(v_{s,t,f} - v) - K_p(s_{v,f} - s_d) 
& \left( 0 \leq s_v \leq s_p \right) \\
-\hat{a} \left( \frac{s'(v, v_f)}{s_f} \right)^2 
& \left( \text{otherwise} \right)
\end{cases}
\]

\(s' = s_0 + \max \left[ 0, vT + \frac{v - v_f}{2 \sqrt{ab}} \right] \)

where \(\hat{v}_{s,t,f} \), \(v_{s,t,f} \), and \(s_{v,f} \) are the nearest preceding vehi-

cle’s acceleration, velocity, and V2V distance, respectively,
relative to the vehicle of interest when two roads compris-
ing the intersection are artificially duplicated. \(s_d\) indicates
the target artificial V2V distance and is equal to the safety
margin of control. \(K_d\) and \(K_p\) are feedback gains. In addi-
tion, \(s_p\) indicates the distance of the control activation point
from the entrance of the intersection. In other words, this
model simulates driving behavior for automatic driving con-
trol for passing through intersections from the control ac-

4. Simulation Evaluation

This section reports the conditions and results of the evaluation of the simulation models explained in section 3. First, simulation conditions are specified, and the results are then reported.

4.1 Simulation Conditions

The simulation assumed a one-way intersection in which right/left turning is prohibited. Each road connecting to the intersection is 2 km in length and crosses in the point after 1 km. One hundred vehicles are prepared on each road and each vehicle starts to drive in turn at intervals of 2 s to 10 s, which are randomly selected. Each vehicle starts from the endpoint of the road at 40 km/h.

The energy-saving effect of the automatic driving control for passing through intersections is evaluated by specifying that all vehicles drive according to either the manual vehicle behavior model or the controlled vehicle behavior model. Target velocity in the simulation is set to 60 km/h, which is the limiting velocity on a standard highway. The target V2V time is set to 2 s, which is the standard V2V time, and the target V2V distance is set to 4 m, using a recent research project as a reference. In addition, the time when the first vehicle on each road starts to drive at the beginning of the simulation and other parameters common to both models are set to the same values. Moreover, in case all the vehicles drive according to the manual vehicle behavior model, traffic signals are placed at the intersection. The traffic signal at the intersection changes from red to green and vice versa every 60 s and indicates different signals to the two intersecting roads. The minimum required energy model of all the vehicles simulated a D segment vehicle.

In addition to the above conditions, the random number that determines the interval time for each vehicle is normally distributed in order to evaluate the relation of the degree of traffic congestion and the energy-saving effect. The simulation software is developed with C, based on the abovementioned manual vehicle behavior model and the controlled vehicle behavior model. Calculation frequency is fixed to 1 ms. A laptop PC with core i7, manufactured by Intel, is used for the simulation.

4.2 Simulation Results

Experimental results are shown in Fig. 3 and 4. Figure 3 shows the velocity of the vehicles in each pattern for the manual vehicle behavior model and the controlled vehicle behavior model in a boxplot. The results show that the controlled vehicle behavior model performs at a higher average velocity than the manual vehicle behavior model. This is because the manual vehicle behavior model needs to stop vehicles in each lane while the controlled vehicle behavior model does not. Conventional traffic control by traffic signals is inferior in terms of efficiency because it makes vehicles in each lane stop even if the vehicles would not cause collisions when vehicles in both lanes do not stop. Although automatic driving control for passing through intersections settles maximum traffic capacity according to a fixed vehicle-to-vehicle distance, it is more efficient because it does not require unnecessary stops. This can also be explained from the result that the scattering in the result of the controlled vehicle behavior model is smaller than that of the manual vehicle behavior.
Automatic driving control for passing through intersections does not cause unnecessary stopping even in the case where vehicles flow into an intersection at random.

Figure 4 shows the fuel consumption of the vehicles in each pattern pf for the manual vehicle behavior model and the controlled vehicle behavior model in a boxplot. The result shows that the controlled vehicle behavior model performs less fuel consumption than the manual vehicle behavior model. Clearly, the controlled vehicle behavior model does not require vehicles to stop unnecessarily, thereby reducing unnecessary fuel consumption. In addition, even in the case where vehicles flow into the intersection at random times, the scattering of results of the controlled vehicle behavior model is smaller. This result confirms that automatic driving control for passing through intersections can yield an energy-saving effect compared with traffic control using conventional traffic signals in several situations.

The above results verified that automatic driving control for passing through intersections has the effect of decreasing traffic congestion. In addition, they clarified that automatic driving control for passing though intersections can be expected to achieve a secondary effect for energy saving because driving control can clear congestion at intersections.

5. Conclusions

This paper reported on the energy-saving effect provided by automated driving control for passing through intersections.

Specifically, the introduction explained that quantitative evaluation for benefit of the driving control to users is required for accomplishing automated driving control of vehicles. Then related works on vehicle control for saving energy is introduced. Many related works on the driving control model have been conducted; however, none have previously addressed the problem of interest in this paper. Details of the manual vehicle behavior model based on the IDM and the controlled vehicle behavior model, which are developed for evaluation of the energy-saving effect of the automatic driving control for passing through intersection, were described. Finally, the simulation evaluation on energy-saving effect of the automatic driving control for passing through intersection using the simulation models is reported.

In future work, we plan to evaluate the energy-saving effect of automatic driving control for passing through intersections in more complex situations.

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References


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