A Generation Method of Speed Pattern of Electric Vehicle for Improving Passenger Ride Comfort

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Abstract: This paper deals with the passenger ride comfort of electric vehicle. A generation method of speed pattern is proposed for improving the ride comfort against the longitudinal acceleration/deceleration. The speed pattern generated using proposed technique is based on the general optimal control theory with evaluating the acceleration and the jerk which is time derivative of the acceleration. The effectiveness of the present method is demonstrated through numerical experiments.

1 INTRODUCTION

From the point of view of preventing a motion sickness and an accident, the ride comfort of the car is very important(Nozaki, 2008). Because vibration influences ride comfort, many studies are performed about the relation of vibration and ride quality from the past(Akatsu, 1998; Cucuz, 1994). An active suspension control system (Itagaki et al., 2013) is a typical example.

However, these studies are mainly investigated on ride comfort against the vibration in the vertical direction, and there are few study on ride discomfort due to longitudinal acceleration/deceleration or tuning motion. As well as the vibration, it is important to consider the influence on lateral speed change for improving overall ride comfort.

Therefore, in this paper, we propose the generation method of longitudinal speed pattern using the jerk which is time derivative of the acceleration and the acceleration as the evaluation index, for improving the ride comfort against the longitudinal acceleration/deceleration. The proposed method aims to contribute to improvement of beginner driver's driving skill from the viewpoint of passenger's comfortability by showing the ideal running pattern and checking the driving.

An electric vehicle (EV) is made the target in this paper. Since EVs have several advantages, compared with the internal-combustion engines (ICEs), as follows (Brown et al., 2010; Tseng et al., 2013).

1) The input/output response is faster than for gasolinediesel engines. It is said that the motor torque response is 2 orders of magnitude faster than that of the engine. E.g., if engine torque response costs 500 ms, the response time of motor toque will be 5 ms.
2) The torque generated in the wheels can be detected relatively accurately. For engine, the output torque varies along with the temperature and revolutions, even it has high-nonlinearity. Consequently the value of torque is too difficult to be measured accurately. However, the value of motor torque is surveyed easily and accurately from the view of current control.
3) The motor can be made small enough, then the vehicles can be made smaller by using multiple motors placed closer to the wheels. The drive wheels can be controlled fully and independently. E.g., it becomes easily achievable to control the differences of driving force developed between the left and right wheel.

From these good points of EVs, we can realize the superior running of vehicle with the good ride comfort by using the proposed speed pattern. Also, it can be applied some type of autonomous vehicle, for example, PRT (Personal Rapid Transit) and so on.

The rest of this paper is organized as follows: Section 2 states the evaluation of ride comfort. In Section

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3, the proposed generation method of speed pattern is presented. The extended proposed method is shown and simulation results are discussed in Section 4. Finally, we end the paper with some conclusions and future work in Section 5.

2 EVALUATION OF RIDE COMFORT

There are various factors which have an influence on ride quality, but the index of the ride quality depends on individuals. About the railroad carriage, various research about the evaluation of the ride comfort with respect to the frequency of vibrations in vertical and horizontal directions have been reported (Nakagawa, 2010).

However, most of these deal with the evaluation of ride comfort with respect to the sustained vibration of the steady run or vibration in the vertical direction. In the case of EVs, it is important to evaluate the ride comfort with respect to lateral speed change. In relation to this point, there are (Wang et al., 2000) and (Wang et al., 2002) as the study which investigated the relation between the acceleration/deceleration , the jerk (time derivative of the acceleration) and ride quality. In (Wang et al., 2000; Wang et al., 2002), subjectivity rating of the ride comfort tests about a start, a stop, immediate start, a run including the hitting the brakes for the resting posture and the reading posture and derive the following linear multiple regression model for the ride comfort index.

$$\begin{aligned} d(t) &= \beta_0 + \beta_1 a_{p+}(t) + \beta_2 a_{p-}(t) \\ &\quad + \beta_3 j_{r+}(t) + \beta_4 j_{r-}(t) + \varepsilon(t) \end{aligned} \tag{1}$$

where parameters in equation (1) are defined in table 1. And where $a_{p+}(t)$, $a_{p-}(t)$, $j_{r+}(t)$, $j_{r-}(t)$ in $T = (t-3, t)$ are given as follows.

Table 1: Definition of parameters.

$d(t)$	ride comfort index at time t
$a_{p+}(t)$	peak value of acceleration in $T = (t-3, t)$ (3 seconds just before time t)
$a_{p-}(t)$	peak absolute value of deceleration in T
$\bar{j}(T)$	average value of jerk in T
$j_{r+}(t)$	effective value of jerk in the case of positive value of $\bar{j}(T)$
$j_{r-}(t)$	effective value of jerk in the case of negative value of $\bar{j}(T)$
$\varepsilon(t)$	error term
β_0	constant term
β_k	Partial regression coefficient

$$a_{p+}(t) = \begin{cases} \max\limits_{t\in T} a(t), & (|\max\limits_{t\in T} a(t)| \geq |\min\limits_{t\in T} a(t)|) \\ 0, & (|\max\limits_{t\in T} a(t)| < |\min\limits_{t\in T} a(t)|) \end{cases} \tag{2}$$

$$a_{p-}(t) = \begin{cases} 0, & (|\max\limits_{t\in T} a(t)| \geq |\min\limits_{t\in T} a(t)|) \\ \min\limits_{t\in T} a(t), & (|\max\limits_{t\in T} a(t)| < |\min\limits_{t\in T} a(t)|) \end{cases} \tag{3}$$

$$j_{r+}(t) = \begin{cases} \sqrt{\frac{1}{3}\int_{t-3}^{t} j^2(\tau)d\tau}, & (\bar{j}(T) \geq 0) \\ 0, & (\bar{j}(T) < 0) \end{cases} \tag{4}$$

$$j_{r-}(t) = \begin{cases} 0, & (\bar{j}(T) \geq 0) \\ \sqrt{\frac{1}{3}\int_{t-3}^{t} j^2(\tau)d\tau}, & (\bar{j}(T) < 0) \end{cases} \tag{5}$$

Unfortunately, it is not possible to derive the speed pattern by using $d(t)$ directly since the $d(t)$ is ride comfort index at the specific time t derived based on the acceleration and the jerk in the real time. It can't show overall evaluation.

Then we need to consider other index for generating the speed pattern for overall ride comfort. In (Wang et al., 2000; Wang et al., 2002), we can see that the value of deceleration, the value of jerk in deceleration, the value of jerk in acceleration and the value of acceleration have big influence on the ride quality by their order. Therefore, it is important to suppress both of the acceleration/deceleration and the jerk to improve the ride quality and we can build the generation method of speed pattern based on these index.

3 GENERATION METHOD OF SPEED PATTERN

The speed pattern is defined as the ideal speed plan to satisfy various demands/limits for ride comfort, energy efficiency at acceleration, position, time and so on. In (Zhao and Hori, 2006), the speed pattern is derived based on the SMART control method (Mizoshita et al., 2006) by using following evaluation function.

$$J_0 = \int_0^{t_f} (\frac{da}{dt})^2 dt \tag{6}$$

where a is the acceleration and t_f is the terminal time, and where the state-space vehicle model is as

$$\begin{pmatrix} \dot{v} \\ \dot{a} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} v \\ a \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} u \tag{7}$$

However, the acceleration, which is one of the most important factor influenced to the ride quality as I mentioned in Sec. 2, does not include directly in this evaluation function. In addition, a vehicle position is

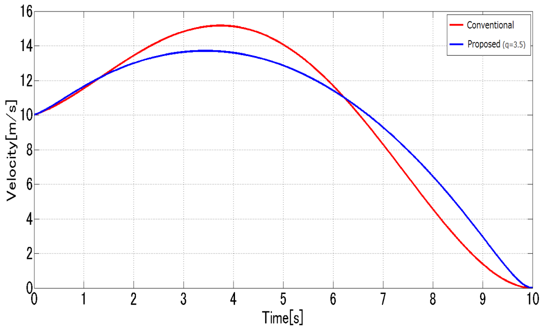

Figure 1: Time response of vehicle speed.

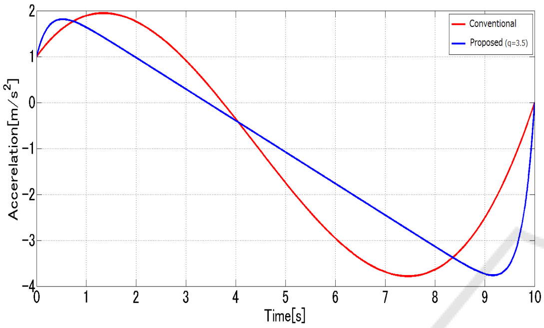

Figure 2: Time response of vehicle acceleration.

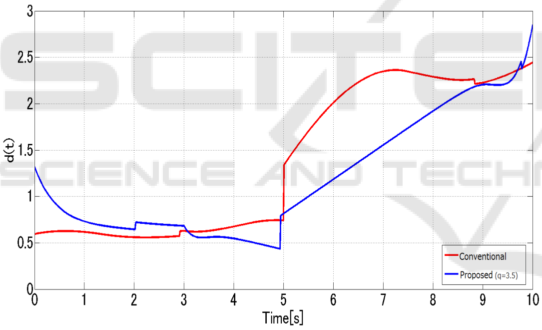

Figure 3: Time response of ride comfort index $d(t)$.

not included in this model. It's important factor for realizing the automatic driving in the near future. From these facts, the state space model and the evaluation function in this paper is defined as follows.

$$\underbrace{\begin{pmatrix} \dot{x} \\ \dot{v} \\ \dot{a} \end{pmatrix}}_{\dot{x}} = \underbrace{\begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}}_{A} \underbrace{\begin{pmatrix} x \\ v \\ a \end{pmatrix}}_{x} + \underbrace{\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}}_{B} u \quad (8)$$

$$J_1 = \int_0^{t_f} \left[(\frac{da}{dt})^2 + q^2 a^2 \right] dt \quad (9)$$

It's also possible to control the vehicle position to add x in the state space variables for automatic driving. Furthermore, we can derive the the speed pattern which emphasized the ride comfort against the acceleration and deceleration by adding the weighted a to evaluation function. (q is the weighting constant.)

Then, by using the generalized optimal control theory, we can derive the following Hamiltonian H from equations (8) and (9).

$$\begin{aligned} H &= \frac{1}{2}(u^2 + a^2) + \lambda^T (Ax + Bu) \\ &= \frac{1}{2}(u^2 + x^T Qx) + \lambda^T (Ax + Bu) \end{aligned} \quad (10)$$

where λ is the Lagrange multiplier and where

$$Q = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & q^2 \end{pmatrix} \quad (11)$$

The solution minimized J_1 is obtained as

$$u = -B^T \lambda \quad (12)$$

Finally we can derive the following speed pattern after deformation of equations with state space equation: $\dot{x} = \frac{\partial H}{\partial \lambda}$, co-state space equation: $\dot{\lambda} = -\frac{\partial H}{\partial x}$ and stationarity equation: $\dot{0} = \frac{\partial H}{\partial u}$.

$$\begin{aligned} x(t) &= C_0 e^{qt} + C_1 e^{-qt} + C_2 t^3 + C_3 t^2 + C_4 t + C_5 \\ v(t) &= qC_0 e^{qt} - qC_1 e^{-qt} + 3C_2 t^2 + 2C_3 t + C_4 \\ a(t) &= q^2 C_0 e^{qt} + q^2 C_1 e^{-qt} + 6C_2 t + 2C_3 \end{aligned} \quad (13)$$

where $C_j (j = 0,1,2,3,4,5)$ are constant coefficients. These values can be decided from initial and terminal conditions for t, x, v and a.

This speed pattern include the method by (Zhao and Hori, 2006).

One example of simulation result is shown to confirm this fact. Let's consider the following initial and terminal conditions.

$$\begin{cases} t_0 = 0 : x_0 = 0, v_0 = 10, a_0 = 1 \\ t_f = 10 : x_f = 100, v_f = 0, a_f = 0 \end{cases} \quad (14)$$

These conditions show the situation that vehicle runs from a state running in speed $10m/s$ and acceleration $1m/s^2$ to the $100m$ spot ten seconds later, and to stop.

In figures 1 ∼ 3, red line indicates the result by the conventional method ((Zhao and Hori, 2006)) and blue line indicates the result by the proposed method with $q = 3.5$ which minimized total sum of $d(t)$.

Figures 1 and 2 show the time response of vehicle speed and acceleration respectively. From these figures, we can see that both methods (the proposed and the method in (Zhao and Hori, 2006)) can generate the speed pattern satisfied initial and terminal conditions.

Figure 3 shows time response of $d(t)$. We can see that the proposed method can suppress the value of $d(t)$ lower than the method in (Zhao and Hori, 2006) in the most part of the whole running period. Therefore, we find out that the proposed method can improve the ride comfort than the method in (Zhao and Hori, 2006).

4 EXTENDED GENERATION METHOD OF SPEED PATTERN

In this section, the proposed method given in Section 3 is extended to the flexible generation method which can cope with the change of terminal conditions in the way of the run for practical use. For example, the method is extended to be able to deal with the situation that it is necessary to shorten a stop spot by some kind of factors such as other vehicles getting into the way. In such situation, the speed pattern should be re-generated in real-time accordance with the change of conditions.

4.1 Extended Method

As the result of many simulations, we see that the remaining run time after the pattern re-generated greatly influenced the quality of ride comfort. Since the change of the run time brings the sudden change of the jerk. Therefore the following evaluation function (J_2) is introduced to decide appropriate remaining run time.

$$J_2 = rx + sy \tag{15}$$

where x is the absolute value of the difference of the value of the jerk just before and after the pattern re-generated, y is the absolute value of the difference of the derivative value of the jerk just before and after the pattern change, and r, s are constant weights. Because it was a problem that the jerk suddenly changes in before and after the pattern re-generated, appropriate values of the weight q of J_1 in equation (9) and the remaining run time are decided by using this evaluation function (J_2 in equation (15) for the change of jerk consecutively and smoothly as much as possible.

In addition, a search range at remaining run time is set. For example, the search range is set as not exceeding the whole running time set beforehand. If the running distance becomes long, remaining run time is able to be increased and search the best values of q and the remaining run time in the enlarged range. Then, it becomes possible to derive the speed pattern with best ride comfort, which minimize the total $d(t)$ in whole running time, against the change of terminal conditions.

4.2 Numerical Examples

Let's confirm the effectiveness of this extended method in some simulations.

Firstly, let's consider the situation that the stop spot is shortened after starting off. The first condition is as follows.

$$\begin{cases} t_0 = 0 : x_0 = 0, v_0 = 0, a_0 = 0 \\ t_f = 10 : x_f = 100, v_f = 0, a_f = 0 \end{cases} \tag{16}$$

Then, at running 60m spot, the stop spot is shortened from 100m to 70m as follows.

$$\begin{cases} t_0 = 0 : x_0 = 60, 0 = v_s, a_0 = a_s \\ t_f = [\text{search}] : x_f = 70, v_f = 0, a_f = 0 \end{cases} \tag{17}$$

where v_s is final speed value before re-generate the speed pattern and a_s is final acceleration value before re-generate the pattern.

The results by the proposed extended method are shown as figures 4 $\sim$ 6. In this simulation, the pattern is re-generated at 5.61s, weights are $q = 2.2, r = 1, s = 0$ and remaining run time after regeneration of pattern is 1.00s.

4.2.1 Simulation I

We can see that the method can cope with the sudden change of stop spot from figures 4 and 5. From figure 6, the ride comfort becomes worse at the time of

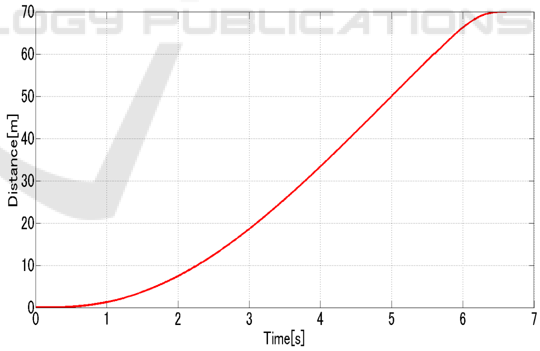

Figure 4: Time response of vehicle position (Simulation I).

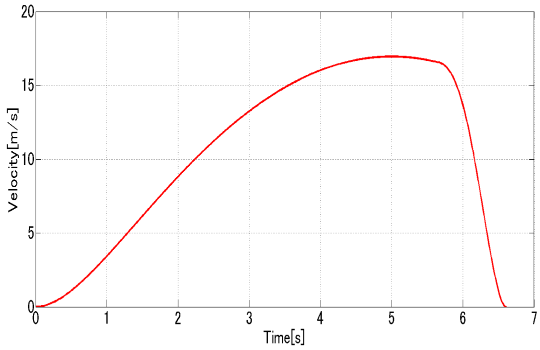

Figure 5: Time response of vehicle speed (Simulation I).

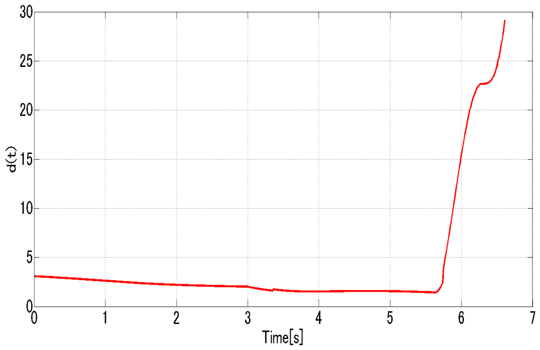

Figure 6: Time response of ride comfort index $d(t)$ (Simulation I).

shortening the stop spot ($5.61s$). But it's natural response due to the sudden shortening of stop distance for safety.

4.2.2 Simulation II

Let's consider the situation that the stop spot is lengthened after starting off. The first conditions as follows.

$$\begin{cases} t_0 = 0 : x_0 = 0, v_0 = 0, a_0 = 0 \\ t_f = 10 : x_f = 100, v_f = 0, a_f = 0 \end{cases} \tag{18}$$

Then, at running $60m$ spot, the stop spot is lengthened from $100m$ to $130m$ as follows.

$$\begin{cases} t_0 = 0 : x_0 = 60, 0 = v_s, a_0 = a_s \\ t_f = [\text{search}] : x_f = 130, v_f = 0, a_f = 0 \end{cases} \tag{19}$$

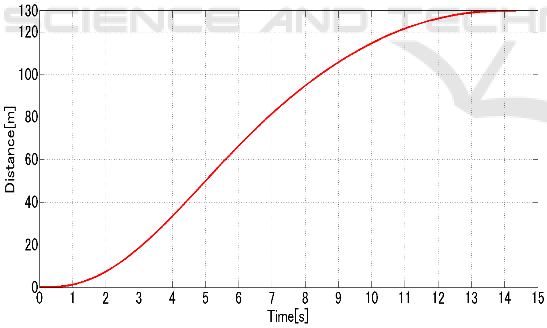

Figure 7: Time response of vehicle position (Simulation II).

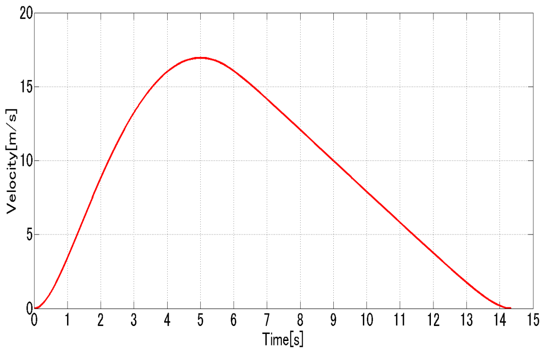

Figure 8: Time response of vehicle speed (Simulation II).

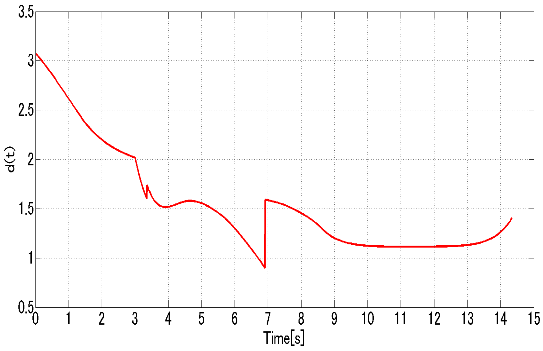

Figure 9: Time response of ride comfort index $d(t)$ (Simulation II).

The results by the proposed extended method are shown in figures 7 $\sim$ 9. In this simulation, the pattern is re-generated at $5.61s$, weights are $q = 1.9, r = 1, s = 0$ and remaining run time after pattern re-generated is $8.173s$.

From these figures, we can see that the method can cope with the situation of lengthening the stop spot. From figure 9, the ride comfort index $d(t)$ turns worse suddenly at about $6.9s$. This is because the absolute value of the acceleration is bigger than the one before $3s$, and it has a big influence on the $d(t)$. But, after $6.9s$ the value of $d(t)$ is suppressed gradually.

4.2.3 Simulation III

In this section, the proposed extended method is compared with the conventional method ((Zhao and Hori, 2006)) in the situation that the stop spot is shortened after starting off. The first condition is as follows.

$$\begin{cases} t_0 = 0 : x_0 = 0, v_0 = 0, a_0 = 0 \\ t_f = 10 : x_f = 100, v_f = 0, a_f = 0 \end{cases} \tag{20}$$

Then, at running $40m$ spot, the stop spot is shortened from $100m$ to $90m$ as follows.

$$\begin{cases} t_0 = 0 : x_0 = 40, 0 = v_s, a_0 = a_s \\ t_f = [\text{search}] : x_f = 90, v_f = 0, a_f = 0 \end{cases} \tag{21}$$

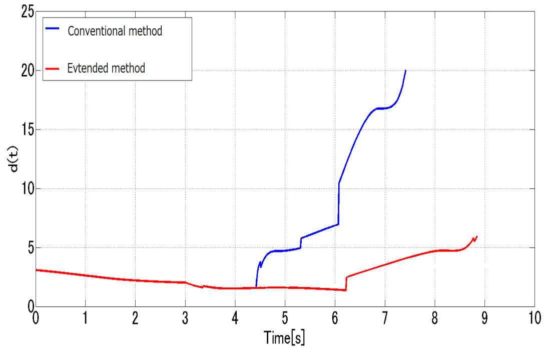

Figure 10: Time response of ride comfort index $d(t)$ (Simulation III).

The result of comfort index $d(t)$ is shown as figure 10 . In this simulation, the conventional method got worse the ride quality after situation changes. On the other hand, the proposed extended method can cope with the change.

5 CONCLUSIONS

In this paper, we have proposed the generation method of speed pattern based on general optimal control theory for improving the passenger ride comfort of electric vehicles. Furthermore, we extend it to the flexible generation method which can cope with the change of terminal conditions in the way of the run.

From simulation results, this extended method can generate the speed pattern flexibly to cope with the change of condition on the way of run. The proposed method can expect to be also useful for the run which emphasized ride comfort of the automatic operation car which would come to practical use in the future. For this, it needs to improved the method based on the proposed techniques(Bianco et al., 2004; Solea and Nunes, 2006; Villagra et al., 2012; Lini et al., 2013) until now.

In future work, the suitability of the method must be studied not only the longitudinal run but also for overall driving situations. Also, it is necessary to verify the effectiveness by actual experiments.

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