Optimal vehicle trajectory planning scheme considering passengers’ comfort for advanced driving assistance

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Abstract. Speed guidance is a significant application in the driver assistance system or driverless automated system. Considering passengers’ comfort under different road conditions, this paper proposes an optimal vehicle speed trajectory planning strategy using the nonlinear programming solution method. In this method, the Pearl curve is taken as the basic model to describe the time-interval characteristics so that the speed and acceleration variation can be further obtained. Taking the weighted dimensionless average accelerated speed and vehicle travelling time as optimal objective, and the speed limit of intersection, speed limit of section, the position of the intersection, the maximum acceleration and deceleration rates, and the arrival time at the downstream intersection as constraints, a multi-variable and single-objective optimization model is built and calculated using Genetic Algorithm after discretization process of the original continuous acceleration variation curve. Results from case study shows that the proposed method presents substantial performance in planning a vehicle trajectory with optimal comfort on the basis that the vehicle arrives the downstream intersection as early as possible.

Keywords: trajectory guidance optimization, passenger’s comfort, Genetic Algorithm, nonlinear programming theory.

1. Introduction

In car-networking environment, dynamic speed guidance is one of the important vehicle management factors which provides the most beneficial speed expected by fully perceiving the road environment and with reliable real-time V2X communication [1-3]. The driver or the vehicle autonomous system controls the vehicle following the suggested speed to obtain certain driving benefits such as reducing the number of stops at an intersection, reducing the fuel consumption, improving the passengers’ comfort and travelling experience.

In dynamic speed guidance, the vehicle trajectory planning is the core strategy which calculates the best suggesting speed for the vehicle. Recently, researches in this field are mainly focused on the
speed trajectory optimization to reduce the number of stops or improve the fuel economy. In [4, 5], the dynamic eco-driving speed guidance strategy (DESGS) is proposed based on dynamic programming by combining real-time vehicle positioning information with signal timing, so as to optimize vehicles’ speed approaching the intersection to reduce energy consumption. In [6], in order to reduce energy consumption and improve comfort, a dynamic programming speed control algorithm based on discrete distance and discrete time strategies is proposed. In [7], a method of collaborative optimization of traffic signal timing and vehicles’ speed trajectory is proposed, which not only minimizes the total travel time of all vehicles, but also improve the fuel economy of individual vehicles. Considering the signal timing states and the queuing length of intersection, some dynamic speed guidance models are also proposed for the purpose of improving traffic capacity in the intersection. In [8], authors use V2I to collect vehicle position, acceleration, speed and other information in real-time, and proposed a two-stage multi-agent vehicle speed optimization control model, which can improve the traffic efficiency at intersections and reduce delay and stopping time. In [9, 10], in order to reduce the average number of stops at multiple intersections, a speed guidance strategy is introduced into a car-following model. The related research takes the intersection queue length as the known constraint condition and does not provide the estimation method of queue dissipation time.

However, these studies rarely consider the comfort of drivers and passengers. Aiming at the problem of speed guidance based on riding comfort, in [11], in order to improve the vehicle comfort and reduce fuel consumption, a new multi-objective adaptive cruise control (ACC) optimization strategy under the framework of model predictive control (MPC) was established with the vehicle acceleration value and its rate of change as constraints. In [12], a set of speed control strategies to improve comfort from the perspective of driving safety and according to the various transient modes between different velocity is presented. In [13], authors suggested that Green Light Optimal Speed Advisory (GLOSA) should be used to adjust the speed of the bus so that it can reach the intersection when the light is green. It is evident from these studies that, they did not carry out a targeted smoothness analysis and speed guidance for sections containing intersections.

This paper proposes an optimal vehicle trajectory planning scheme considering comfort level described by the acceleration changes. The rest of the paper is organized as follows. The trajectory optimization model based on nonlinear programming including optimal objective theory and the constraints are introduced in Section II. In Section III, the model calculation method using Genetic Algorithm is proposed. In Section IV, the proposed method is verified and the results are analyzed. Finally, in Section V, we conclude the paper and provide the discussions for future work.

Figure 1. The time-distance feature of a vehicle moving between two adjacent intersections.

2. Trajectory optimization model based on ride comfort
The main purpose of vehicle speed guidance is to provide a rational advisory speed to driver or the unmanned control system, enabling vehicle to pass through the downstream intersection without stopping in the green time period.

When a vehicle is in the state of driving between two intersections, the vehicle will move forward in an accelerating state firstly, and it will stop accelerating when the speed reaches to its peak. Afterwards, the vehicle will slow down slowly to reach the next intersection. In ideal conditions that
there are no abnormal interferences during the process, the turning point of acceleration, that is, the peak moment of speed, generally appears in the center and middle moment of the whole driving process. Between two adjacent intersections, the time-distance feature of a vehicle moving as figure 1.

The position of the vehicle changes slowly in the early stage; in the mid-term, the change in speed is faster; in the later stage, the change in speed tends to be slower. According to the driving principles of the above three stages, we present the foundation trajectory modelling method based on the Pearl curve, as shown in equation (1).

\[
f(t) = \frac{L_{\text{max}}}{1 + e^{-\frac{t}{\theta_1}}} \left(1 + e^{-\frac{t}{\theta_2}}\right)^{\theta_3}
\]

In equation (1), \(L_{\text{max}}\) is the road length. \(\theta_1\) and \(\theta_2\) are the accommodation coefficients.

Approximately, we assume the time-distance trajectory is symmetrical about \((k, f(k))\), where \(k\) is the critical point time. The relationship between vehicle travelling time \(t_d\) and \(t_k\) satisfies is \(t_d = 2t_k\).

### 2.1 Optimal objective

Based on the foundation trajectory model presented in equation (1), we propose the optimal objective for vehicle speed trajectory planning in this subsection. Taking the derivative of equation (1), the vehicle speed variation curve can be acquired, as shown in equation (2).

\[
v(t) = f'(t) = \frac{\theta_2 L_{\text{max}} e^{-\frac{t}{\theta_1}}}{\theta_1 \left(1 + e^{-\frac{t}{\theta_2}}\right)^{\theta_3+1}}
\]

Taking the derivative of equation (2) and the vehicle acceleration variation is equation (3).

\[
a(t) = f''(t) = \frac{\theta_1 L_{\text{max}} \left(\theta_2 + 1\right) e^{-\frac{t}{\theta_1}} - e^{-\frac{t}{\theta_2}}(1 + e^{-\frac{t}{\theta_2}})}{\theta_1^2 \left(1 + e^{-\frac{t}{\theta_2}}\right)^{\theta_3+2}}
\]

While driving a vehicle, the driver or the automatic driving control system follows the optimal speed guidance planning scheme to satisfy certain requirements. On one hand, the vehicle should pass through the road with a minimal travelling delay. On the other hand, the driver and passengers can avail a most comfortable experience. The former can be expressed by the vehicle travelling time \(t_d\). For the latter, it can be expressed by the average variation of accelerated speed during the driving process. Referring to equation (3), the average accelerated speed is calculated by equation (4).

\[
\bar{a}(t) = \frac{\int_0^{2t_k} |f''(t)|}{2t_k} = \frac{\int_0^{2t_k} \left(\theta_2 + 1\right) e^{-\frac{t}{\theta_1}} - e^{-\frac{t}{\theta_2}}(1 + e^{-\frac{t}{\theta_2}})}{\theta_1^2 \left(1 + e^{-\frac{t}{\theta_2}}\right)^{\theta_3+2}}
\]

Based on the above analysis, the optimal objective of vehicle trajectory planning proposed in this paper is shown as follows:

\[
\text{obj} : \min (a\bar{a} + \beta \bar{t}_d)
\]

Where \(\bar{a}\) and \(\bar{t}_d\) denote the dimensionless average accelerated speed and vehicle travelling time which are calculated by equation (6). \(\alpha\) and \(\beta\) are the weighting coefficients.

\[
\bar{a} = \frac{a(t) - [a(t)]_{\text{min}}}{[a(t)]_{\text{max}} - [a(t)]_{\text{min}}} \quad \text{and} \quad \bar{t}_d = \frac{t_d - t_{\text{min}}}{t_{\text{max}} - t_{\text{min}}}
\]

Where \([a(t)]_{\text{max}}\) and \([a(t)]_{\text{min}}\) denote maximum and minimum average accelerated speed
respectively in the feasible solution domain under the constraints. Taking the departure time of the vehicle from the upstream intersection as the zero reference in equation (6), \( t_{\text{min}} \) denotes the starting time of green phase in the downstream intersection, and \( t_{\text{max}} \) denotes the end time. And \( t_{d} \) is the vehicle travelling time.

When the guided vehicle accelerates from zero-speed to the tolerant maximum speed in the shortest time, it gets a maximum average accelerated speed. Suppose the road speed limit is \( v_{\text{max}} \), and the \( t_{\text{min}} \) is the earliest time for the vehicle to reach the downstream intersection which is corresponding to the signal timing plan, the \( \dot{u}(t) \) can be calculated by \( \dot{u}(t)_{\text{max}} = \frac{v_{\text{max}}}{t_{\text{min}}} \).

2.2 Constraints

When the test vehicle is guided on the road between adjacent intersections, its driving trajectory is restricted by equation (1) the road environment conditions, including the speed limit of intersection, the speed limit of section, the position of intersections, and travel time conditions, mainly the tolerant maximum acceleration and deceleration. The details of the constraints are analysed as follows:

(1) Constraints by intersection speed limit

When the test vehicle is in the position of intersection, its speed should be lesser than the limit value of the intersection. When \( t=0 \) and \( t=2t_{k} \), the values of equation (2) should satisfy equation (7).

\[
\begin{align*}
\lim_{t=0} f(t) &\leq v_{\text{lim}}^{1} \\
\lim_{t=2t_{k}} f(t) &\leq v_{\text{lim}}^{1}
\end{align*}
\]

Where \( v_{\text{lim}}^{1} \) denotes the speed limit value of intersection. Equation (10) can be further expressed by equation (8).

\[
\frac{\dot{\varphi}_{1}L_{\text{max}}e^{\frac{q_{1}}{t_{k}}}}{\theta_{1}(1+e^{\frac{q_{1}}{t_{k}}})^{\phi_{1}+1}} \leq v_{\text{lim}}^{1} \quad \text{and} \quad \frac{\dot{\varphi}_{1}L_{\text{max}}e^{\frac{-q_{1}}{t_{k}}}}{\theta_{1}(1+e^{\frac{-q_{1}}{t_{k}}})^{\phi_{1}+1}} \leq v_{\text{lim}}^{1}
\]

(2) Constraints by section speed limit

When the test vehicle is in any arbitrary position of the section, its speed should be lower than the limit value of the section. During the driving time period \((0,2t_{k})\), the values of equation (2) should satisfy equation (9).

\[
\begin{align*}
\lim_{t_{(0,2t_{k})}} f(t) &\leq v_{\text{lim}}^{2} \\
\lim_{t_{(0,2t_{k})}} f(t) &\leq v_{\text{lim}}^{2}
\end{align*}
\]

(3) Constraints by the position of intersection

The Pearl curve is used as the foundation model in this study to describe the optimal driving trajectory. However, as presented in Figure 1, at the two ends of the domain of definition \((t=0, t=2t_{k})\), the proposed Pearl model curve can only approximate to the initial position \( L=0 \) and the final position \( L=L_{\text{max}} \), but can’t reach the endpoints. In order to solve this problem, a minimum tolerant distance \( \varepsilon >0 \) is defined to make the Pearl model curve identical with actual condition. When \( t=0 \) or \( t=2t_{k} \), and the distance between the vehicle and the initial position \( L=0 \), or the final position \( L=L_{\text{max}} \) is smaller than \( \varepsilon \), the test vehicle can be considered as driving at the intersection. Hence, the constraints caused by the position of the intersection is expressed by equation (10).

\[
\begin{align*}
f(t)_{|_{t=0}} &= \frac{L_{\text{max}}}{(1+e^{\frac{-q_{1}}{t_{k}}})^{\phi_{1}}} - \varepsilon \quad \text{and} \quad L_{\text{max}} - f(t)_{|_{t=2t_{k}}} = \frac{L_{\text{max}}}{(1+e^{\frac{q_{1}}{t_{k}}})^{\phi_{1}}} - \varepsilon \leq \varepsilon
\end{align*}
\]

(4) Constraints by the maximum acceleration and deceleration rates

During the speed guiding progress, the vehicle acceleration rate should be less than the allowed
maximum value and deceleration rate should be larger than the minimum value where the maximum and minimum values are constrained by the performance of the vehicle itself. In the domain of definition \([0, 2t_k]\) should satisfy:

\[
a_{\text{min}} \leq f''(t) = \frac{\theta_2 L_{\text{max}}}{\theta_1^2} \left( \theta_2 + 1 \right) e^{\frac{-2t + 2t_k}{\eta \eta_k}} e^{\frac{-t + t_k}{\eta \eta_k}} (1 + e^{\frac{-t + t_k}{\eta \eta_k}}) \leq a_{\text{max}}
\]

(11)

(5) Constraints by the arrival time at the downstream intersection

To acquire the benefit that the vehicle to be guided can pass the downstream intersection without stopping, the arrival time should be during the green time period of its travelling phase. The constraints by the arriving time are expressed by equation (12).

\[
t_{\text{min}} \leq t_k \leq t_{\text{max}}
\]

(12)

3. Model solution based on GA

The problem to be solved in this paper is precisely a nonlinear complex objective function. GA is appropriated for solving this kind of problem in conducive to finding the global optimal point and reducing the risk of falling into the local optimal solution. In the course of dynamic speed guidance, the optimal recommended driving speed is calculated using cloud platform and provided to the vehicle at an interval time. The total control period \([0, 2t_k]\) is divided into units of time series by \(\Delta t\), as shown in Figure 2.

**Figure 2.** Discretization of vehicle acceleration function.

In the minimal control granularity, the test vehicle is assumed to be driving at a constant speed. Equation (4) can be further expressed as follows:

\[
\sum_{i=1}^{N} \frac{\theta_2 L_{\text{max}}}{\theta_1^2} \left( \theta_2 + 1 \right) e^{\frac{-2(i-1)\Delta t + 2t_k}{\eta \eta_k}} e^{\frac{-(i-1)\Delta t + t_k}{\eta \eta_k}} (1 + e^{\frac{-(i-1)\Delta t + t_k}{\eta \eta_k}}) = \frac{\sum_{i=1}^{N} \theta_2 L_{\text{max}}}{\theta_1^2} \left( \theta_2 + 1 \right) e^{\frac{-2(i-1)\Delta t + 2t_k}{\eta \eta_k}} e^{\frac{-(i-1)\Delta t + t_k}{\eta \eta_k}} (1 + e^{\frac{-(i-1)\Delta t + t_k}{\eta \eta_k}}) (1 + e^{\frac{-t + t_k}{\eta \eta_k}}) = \frac{\sum_{i=1}^{N} \theta_2 L_{\text{max}}}{\theta_1^2} \left( \theta_2 + 1 \right) e^{\frac{-2(i-1)\Delta t + 2t_k}{\eta \eta_k}} e^{\frac{-(i-1)\Delta t + t_k}{\eta \eta_k}} (1 + e^{\frac{-(i-1)\Delta t + t_k}{\eta \eta_k}}) (1 + e^{\frac{-t + t_k}{\eta \eta_k}}) \theta_k^{2} + 2
\]

(13)

Where \( N \) is the number of time intervals in the series.

Hence, the optimal objective presented in equation (5) can be further expressed as follow:

\[
\text{obj} : \min \left[ \alpha \frac{\sum_{i=1}^{N} \theta_2 L_{\text{max}}}{\theta_1^2} \left( \theta_2 + 1 \right) e^{\frac{-2(i-1)\Delta t + 2t_k}{\eta \eta_k}} e^{\frac{-(i-1)\Delta t + t_k}{\eta \eta_k}} (1 + e^{\frac{-(i-1)\Delta t + t_k}{\eta \eta_k}}) (1 + e^{\frac{-t + t_k}{\eta \eta_k}}) \theta_k^{2} + 2 \right] + \beta \left[ \frac{t_k - t_{\text{min}}}{\max \left[ \frac{1}{\eta_k} \right] - \min \left[ \frac{1}{\eta_k} \right]} \right]
\]

(14)
Referring to equation (14), the vehicle speed trajectory optimization can be considered as a multi-variable and single-objective optimization problem. The variables for solution include $t_k$, $\theta_1$ and $\theta_2$.

The solution process of the proposed model based on GA is presented as follows:

(i) Calibrate the $[a(0)]_{\text{max}}$ and $[a(0)]_{\text{min}}$ according to the speed limit of the road section and the signal timing plan of the downstream intersection.

(ii) Get $t_{\text{max}}$ and $t_{\text{min}}$ based on the green time plan of the downstream intersection, and further build the optimal objective function referring to equation (14) combined with the values acquired in Step 1.

(iii) Calculate the values of $t_k$, $\theta_1$ and $\theta_2$ using GA, achieving the optimal vehicle speed trajectory planning.

4. Case study

4.1 Introduction to the Simulation Scenario

An arterial road with two intersections is selected for the case study. The road configuration parameters and the corresponding parameters of the model solution are introduced in Table 1.

Table 1. Configuration parameters of the road and model.

| Category                        | Parameter                                      | Value  |
|---------------------------------|------------------------------------------------|--------|
| Basic road configuration        | Road length (m)                                | 500    |
|                                 | Speed limit of 1st intersection (km/h)         | 30     |
|                                 | Speed limit of 2nd intersection (km/h)         | 30     |
|                                 | Speed limit of the section (km/h)              | 60     |
| Vehicle motion characteristics  | Maximum acceleration $[14]$ (m/s$^2$)          | 2.7    |
|                                 | Maximum deceleration $[15]$ (m/s$^2$)          | -1.5   |
| Timing plan of the intersection | Time cycle (s)                                 | 120    |
|                                 | Phase length (s)                               | 30     |
|                                 | Offset (s)                                     | 0, 20, 40, 60, 80, 100 |
| Parameters of the model solution| Minimum tolerant distance error $\varepsilon$ (m) | 10     |
|                                 | Minimum tolerant acceleration error $\delta$ (m/s$^2$) | 0.05   |
|                                 | Initial population size                        | 500    |
|                                 | Mutation probability                           | 0.1    |
|                                 | Crossover probability                          | 0.9    |

4.2 Model solution results based on GA

According to the configurations of the simulation scenario presented in Table 1, the case vehicle may arrive at downstream intersection during two signal timing cycles, and the possible solution domain is analysed and presented in Figure 3.

Figure 3. The possible solution domain for different cases.
Referring to the cases shown in Figure 3, the maximum average accelerated speed \( \max(a(t)) \) is calculated under different offset conditions and shown in Table 2.

Table 2. Values of Under Different Cases.

| Arrival time | The first signal timing cycle \((0 \leq t_{k1} \leq 120)\) | The second signal timing cycle \((120 \leq t_{k2} \leq 240)\) |
|--------------|---------------------------------|---------------------------------|
| Offset \( t_{\min} \) (s) | 0     20  40  60  80  100  | 0     20  40  60  80  |
| \( a(t) \) max (m/s^2) | /   1.67 0.83 0.56 0.42 0.33 | 0.28 0.24 0.21 0.19 0.17 |

As shown in Figure 3 and Table 2, when the offset is 0, the starting time of green phase in the downstream intersection is also 0, which is insignificant in actual scenario. Besides, since the speed limit of the section is 60 km/h (16.7 m/s), the minimum travelling time for the vehicle to arrive at the downstream intersection is larger than 30 s at the maximum travelling speed in the simulation scenario. Hence, there is no effective solution when \( t_{\min} \) is less than 15 s. When these cases happen, it indicates that, there is insufficient time for the guided vehicle to reach the downstream intersection during the green time in the first signal timing cycle.

When the offset is set 60, \( t_{k2} \in [30, 45] \), the mutation probability \( P_m \) changes from 0.01 to 0.15, the calculation process and the optimization solution values are presented in Figure 4.

![Figure 4. The iterative process under different mutation probability cases.](image)

In Figure 4, the calculation process presents a fast convergence trend and the final results show minor steady residual errors under different mutation probability values. The solutions of the trajectory optimization problem present suitable population diversity characteristics and no obvious premature phenomenon occurs. When the mutation probability is 0.1, the iterative convergence curve shows more gradual tendency compared with other cases. In this paper, the mutation of probability 0.1 is taken to further calculate the optimal \( t_{k1}, \theta_1 \) and \( \theta_2 \).

4.3 Results and analysis of trajectory optimization

Under different offset values, the calculation process and the optimization solution values are presented in Figure 5.

In Figure 5, it is evident that all the cases achieve fast convergence in 30 generations that is also consistent with the results presented in Section 4.2. Generally, the vehicle travels to the downstream intersection in a shorter time under the same initial velocity and road speed limit. This shows, it must operate with larger speed variation and average acceleration, and definitely shows uncomfortable travelling experience. Otherwise, if the guided vehicle has sufficient time to reach the downstream intersection with a slow acceleration, the driver and passenger can feel higher comfort. All these sound and practical conclusions are consistent with the results of optimized acceleration values under different offsets which present different travelling time for the guided vehicle.
Figure 5. The iterative process under different offset cases.

Referring to the results of parameters $t_i$, $\theta_1$ and $\theta_2$ calculated by GA under different offset cases mentioned above, the optimal time-distance trajectories, speed trajectories and acceleration trajectories are presented in Figure 6.

Figure 6. The optimal trajectories under different offset values.

As shown in Figure 6, when the phase value is between 0 and 100, the $2t_i$ of the minimum convergence time of each phase is 120, 140, 64, 80, 88, and 100 respectively, which verifies the feasibility of the GA to solve the optimal trajectory parameter. When the phase values are 0 and 20 respectively and the $2t_i$ is from 0 to 120, there is no optimal solution. Therefore, when the phase value is 0 or 20, the minimum convergence time $2t_i$ is 120 and 140, respectively. At the same time, according to the results from graphs, when the phase is 40, 60 and 80, the value of the convergence time is inside the phase interval, and when the phase is 0, 20 and 100, the value of the convergence time is the minimum value of the phase interval. The value of convergence time $2t_i$ is inside the phase interval. When the phase is 0, 20, and 100, the value of convergence time is the minimum value of the phase interval.

In Figure 6, under different offsets, the time-distance curves change relatively gentle, and the fluctuation of velocity and acceleration is minimum. The acceleration disturbance value $\sigma$ is used as the quantitative evaluation index of driving comfort level which is calculated by Equation (15).

$$\sigma = \left[ \frac{1}{N} \sum_{i=1}^{N} (a_i - \bar{a})^2 \right]^{1/2}$$

In equation (15), $a_i$ is the acceleration at time $i$, and $\bar{a}$ is the average acceleration.
When $\sigma$ becomes larger, the riding comfort level gets worse. Whereas for the smaller $\sigma$, the riding comfort level becomes better. The corresponding relationship between different acceleration interference values $\sigma$ and riding comfort level [16] is shown in Table 3.

**Table 3.** Riding comfort level classification based on acceleration disturbance value $\sigma$.

| Acceleration interference value $\sigma$ | Ride comfort Criteria |
|----------------------------------------|----------------------|
| $\sigma \geq 0.4572 \text{ m/s}^2$     | Uncomfortable        |
| $0.2134 \text{ m/s}^2 \leq \sigma \leq 0.4572 \text{ m/s}^2$ | Slightly Uncomfortable |
| $\sigma \leq 0.2134 \text{ m/s}^2$     | Comfortable          |

When the vehicle runs under the minimum convergence time of each offset, the acceleration interference value $\sigma$ is calculated and results are shown Table 4.

**Table 4.** Acceleration interference value $\sigma$ under the minimum convergence time of each offset.

| Offset | 0  | 20 | 40 | 60 | 80 | 100 |
|--------|----|----|----|----|----|-----|
| Acceleration interference value $\sigma$ (m/s$^2$) | 0.065 | 0.06 | 0.09 | 0.08 | 0.076 | 0.071 |

From Table 4, it is evident that when solving the optimal velocity guidance by GA, the acceleration interference values are all less than 0.2134 m/s$^2$, which is within high comfort range. With the increase of $2t_i$, the disturbance value of acceleration decreases $\sigma$ and comfort level increases.

5. Conclusions and Future Works

It is significant to consider the passengers comfort in advanced driving assistance systems. Problems exists especially when a when a vehicle pass through an intersection without stopping. To deal with such incurring situations, an optimal vehicle trajectory scheme considering passenger comfort is proposed in this paper. In the process of obtaining solution, the optimal speed is obtained by using GA, and factors such as intersection speed limit, section speed limit and ride comfort parameters are added. Through simulation using Python, the parameters of optimal trajectory can be obtained, and the optimal time-distance curve, velocity curve and acceleration curve of each phase can be generated to meet the requirements of maximum comfort level.

The main purpose of this paper is to present an ideal referenced optimization trajectory for driver assistance or driverless automated system to get a relative comfort driving experience. In application, the results can be used in the trajectory planning before the vehicle is guided. However, when the vehicle is driving on road, abnormal interferences may occur during the driving period. Hence, the future work mainly focuses on the real-time dynamic control scheme which takes the optimal trajectory obtained in the paper as the target.

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