Development of Fuel-Efficient Driving Strategies for Adaptive Cruise Control

Mohammad Mamouei*, Ioannis Kaparias, George Halikias

School of Engineering and Mathematical Sciences, City University London

*** Email: Mohammad.Mamouei.1@city.ac.uk**

Introduction

This paper investigates the effect of different driving parameters (e.g. acceleration behaviour, safe time headway, desired velocity, etc.) on the fuel consumption of individual vehicles under typical urban driving conditions, and proposes a fuel-efficient driving strategy. The effects of such a strategy on other critical features in the traffic network, such as traffic capacity, local stability, and safety, are discussed.

The study is based on the Intelligent Driving Model (IDM) [1], which allows for an extensive investigation of several driving strategies due to the small number of parameters and the model's computational efficiency. The most influential parameters with respect to fuel consumption are identified, and even though they are model-specific, their function forms the core of any car-following model, and by extension of any Adaptive Cruise Control (ACC) system. As such, the study helps gain insight into incorporating fuel efficiency in ACC systems, regardless of the model specificities. The conclusions with respect to improving fuel efficiency, drawn here, can be used in any advisory system, or even "manually" by individual drivers.

Car-Following

The IDM has been selected for the present study on the basis of a number of advantages that it presents over others, such as the MITSIM car-following model [2, 3], Wiedemann [4], the Gipps acceleration model [5], and the General Motors (GM) model and its several extensions [6]. Specifically, IDM can successfully reproduce the most subtle characteristics of traffic flow observed in real traffic (such as triggered stop-and go waves, oscillatory congested traffic, etc.), it is collision-free, and it has been already implemented in real test cars as an ACC system with some enhancements [1, 7]. Moreover, it is computationally simple and relies on a small number of parameters, each with an intuitive meaning, and also enables thorough analysis of the macroscopic effects of changing model parameters in terms of capacity, stability, and safety, as has already been carried out [1, 8].

This model is given by following general equation;

$$\dot{v} = a[1 - \left(\frac{v}{v^d}\right)^{\delta} - \left(\frac{s^*(v, \Delta v)}{s}\right)^2]$$

$$s^*(v, \Delta v) = s_0 + s_1\sqrt{\frac{v}{v^d}} + Tv + \frac{v\Delta v}{2\sqrt{ab}}$$

$$\Delta v = v - v_p$$

where, a is maximum acceleration , v^d is desired speed, δ is acceleration exponent, s_0 and s_1 determine jam distances in fully stopped traffic and in high densities respectively, T is safe time headway, b is comfortable deceleration, and they are all model parameters. Input variables are speed of the subject vehicle, v, speed of the preceding vehicle, v_p, and distance headway, s. Finally, the output variable , $\dot{v}$, determines the acceleration of the subject vehicle.

Fuel consumption

In the present study, a fuel consumption model has been developed based on VT-micro [9], a model specifically developed for the investigation of fuel consumption at the operational level of driving, taking instantaneous velocity and acceleration as input variables. The new model is a simplified form of VT-micro; it has been developed through the examination of various simplified model structures relative to VT-micro, with the objective of minimising its complexity by eliminating certain parameters without a significant loss of accuracy. A suitable model structure has been identified and has been estimated using data derived from VT-micro over the whole envelope of acceptable accelerations and velocities. The results of the estimation have shown that the simplified model achieves high accuracy in both the prediction of fuel consumption for the overall envelope of accelerations and velocities, and for the US Motor Vehicle Emissions Federal Test Procedure (FTP) drive cycle [10] compared to the VT-micro predicted values ($R^2 = 0.9988$ and $R^2 = 0.94$ respectively). This is illustrated in Figure 1.

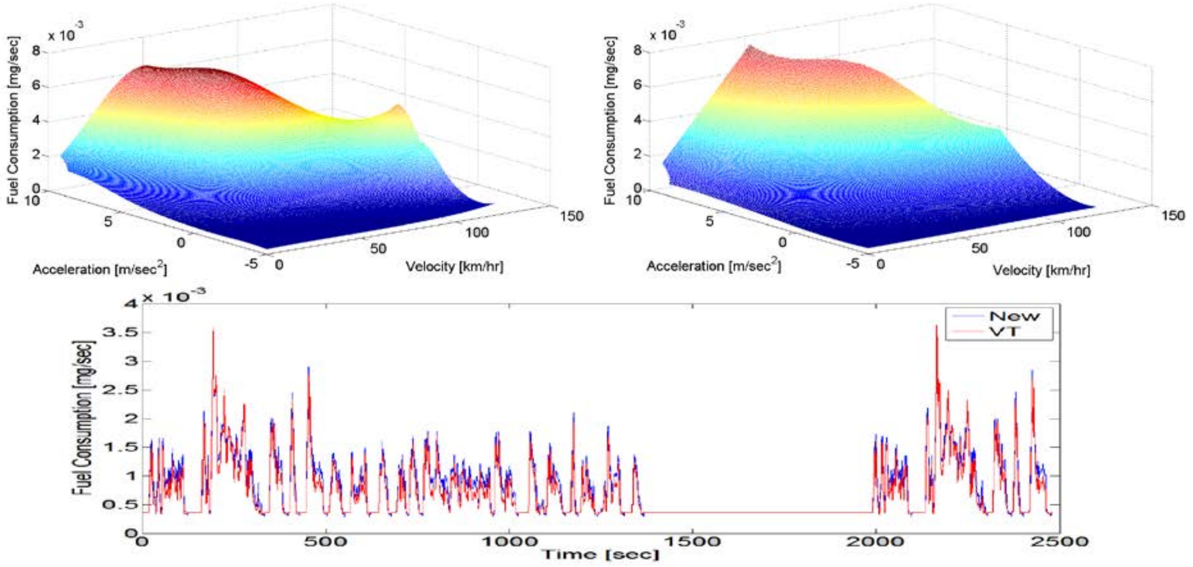

Figure 1: Comparison of fuel consumption prediction between VT-micro and simplified model: a) Fuel consumption using VT-micro for different velocities and accelerations; b) fuel consumption using new model; c) Instantaneous fuel consumption for the FTP drive cycle, where the blue curve denotes the predicted values using the new simplified model, and the red curve denotes the predicted values using VT-micro

The model significantly simplifies the computation of fuel consumption. Namely, it reduces the regimes from two in the original VT-micro model (one for acceleration and one for deceleration) to one, and it reduces VT-micro's exponential function of thirty-two model parameters to a third degree polynomial function with seven model parameters.

Experiment setup

Different driving strategies can be reproduced using different parameter sets in IDM (e.g. aggressive driving can be reproduced using low values for time headway, high accelerations, high values of comfortable deceleration etc.). In this study, the scenario used to implement and examine different driving strategies for a vehicle in traffic is based on the driver of a lead vehicle driving according to the FTP drive cycle [10], and the vehicle in question following it. The FTP drive cycle entails aggressive accelerations and decelerations, along with multiple stops and starts, which are typical of urban driving.

To determine the most fuel-efficient driving strategy, one needs to search the seven-dimensional parameter space for the optimal solution. However, analysing the parameters by means of extensive evaluation of numerous points in the seven-dimensional parameter space using the aforementioned scenario reveals that some of them have only marginal influence on fuel consumption, and/or that their effect is offset by their negative influence on other criteria. This is summarised in Table 1, where the influence on fuel consumption of any parameter i is expressed by the Index of Influence on Fuel Consumption (IIFC), defined as

$$IIFC(i) = 10 \times \frac{S(i)}{\max\limits_{j}(S(j))} \qquad i, j \in [a, b, \delta, v^d, T, s_0, s_1]$$

$$S(i) = \max_{\rho}[CF(i = \rho)] - \min_{\rho}[CF(i = \rho)] \qquad \rho \in [\mathrm{LB(i)} - \mathrm{UB(i)}]$$

where $S(i)$ denotes the maximum reduction in cumulative fuel consumption achieved by varying the parameter i within a reasonable predefined range (as shown in Table 1) in successive runs of the experiment while all other parameters are set to their default values. Here, $CF(i = \rho)$ denotes cumulative fuel consumption obtained at the end of the simulation run with parameter i set to the value ρ and all other parameters set to their default values. Lower and upper boundaries of parameter i are denoted by $LB(i)$ and $UB(i)$ respectively.

Table 1: Importance of different driving parameters on fuel consumption

Parameter	Description	IIFC	range
$a[km/hr^2]$	Maximum acceleration	10	[0.5 - 5]
$b[km/hr^2]$	Desired deceleration	1.5	[0.5 - 5]
δ	Acceleration exponent	0.9	[1 - 10]
$v^d[km/hr]$	Desired velocity	0.7	[60 - 150]
$T[sec]$	Safe time headway	0.5	[0.5 - 10]
$s_0[m]$	Jam distance	≅ 0	[0.5 - 10]
$s_1[m]$	Jam distance	≅ 0	[0 - 5]

From Table 1, hence, it can be seen that the search in the parameter space can be reduced to the three most influential parameters of maximum acceleration a, desired deceleration b and desired speed v^d. Although the acceleration exponent δ has a slightly higher influence than the desired speed v^d, the analysis of this parameter by changing its value in subsequent runs of the experiment whilst keeping the rest of the parameters fixed shows that this parameter needs to be treated with caution, as local stability is sensitive to variations in this parameter and car crashes may occur for values outside a certain range. The boundaries of this range vary with respect to the values of other parameters. The same reasoning justifies excluding the safe time headway parameter T, as increases in this parameter result in a marginal reduction of fuel consumption, but also in a great deterioration of capacity. Furthermore it has been confirmed through the examination of different experimental setups that in less intense stop and start behaviour (i.e. smoother traffic flow), the influence of parameter v^d on fuel consumption increases remarkably. The choice of these control parameters is consistent with what has been previously suggested by Kesting et al [7].

Results and conclusion

The parameter space is searched for the optimal fuel consumption using a genetic algorithm [11], and the result is also confirmed through Monte Carlo simulation. The analysis shows that by choosing the lower boundary values (as indicated in Table 1) for maximum acceleration a, comfortable deceleration b, and desired velocity v^d, fuel consumption reductions of about 12% can be obtained for a single vehicle. Among the aforementioned parameters, maximum acceleration has the highest level of impact on fuel consumption, followed by comfortable deceleration and desired velocity. Furthermore, varying parameters a and b does not affect macroscopic traffic flow features, such as static capacity or density at which maximum capacity is obtained (unlike desired speed), but they both play an important role in local stability. Low values for a and high values for b result in instability. Therefore, while decreasing b for improved fuel consumption can be safe in terms of stability, decreasing a, which can achieve a significant reduction of fuel consumption, should be treated with caution.

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