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A PERSONAL LEVEL DRIVING STRATEGY TO MINIMIZE THE FUEL CONSUMPTION

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Abstract. *This paper discusses an eco-driving strategy on a personal level. It empirically shows how the driving strategy, such as the braking distance, affects gasoline usage. The movement of vehicles in this work is computed by using the car-following model of the optimal velocity model. For the case of vehicles in a platoon, the model is implemented in an agent-based model. From the dynamic vehicle data, we estimate the fuel consumption by a regression model. We analyze cases involving one, two, and twenty vehicles moving in a platoon for various driving strategies. The result shows that strong braking on high vehicle speed leads to a surge in fuel consumption. The efficient driving condition can be maintained at various speeds given the braking distance is adjusted proportionally with speed.*
Keywords: Fuel consumption, Optimal velocity model, Optimal velocity function, Agent-based modeling

1. **Introduction.** Increasing fuel efficiency is one of the current most pressing issues. In line with the Kyoto protocol ratified by 84 nations on Dec. 11, 1997, car manufacturers have to produce vehicles that require less fuel consumption to meet the current and future legislation, and the control of greenhouse gas emissions [1].

For land transportation, various fuel-efficient strategies have been studied. The most widely adopted is by arranging vehicles in a closed distance or platooning where the movement of the vehicles is linked and coordinated by using automated wireless communication technology. The platoon arrangement has many benefits, including cost savings, reduced emissions, enhanced traffic safety, reduced traffic congestion, and more efficient use of road capacity [2]. According to [3, 4], the leading vehicle in a platoon consumed less fuel by six percent. The followers saved ten percent. Thus, platooning increases efficiency substantially.

Moreover, the fuel-efficient platooning was studied by means of mathematical programming solved by genetic algorithm [5], particle swarm optimization [6], and ant colony optimization [7]. In [5], they found the fuel efficiency increased linearly from 1.5% for 10 trucks to 5.0% for 50 trucks.

The fuel-efficient driving strategy has also been studied in the context of an automated constellation of vehicles where the driving can be entirely made automatically. In this environment, [8, 9] proposed an optimum driving strategy by solving an optimal control problem. With such a sophisticated level of control, a complex driving strategy was advised. It reduced fuel consumption by 5%–30%. In general, [8] imparted the efficiency could be achieved by driving at a lower and constant speed, reducing the aerodynamic drag. The reference also found that chatting control of the engine had the potential for energy saving. Finally, better fuel consumption can also be achieved by increasing engine

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efficiency. [1] showed that the use of simple variable valve timing was effective to reduce pumping losses and fuel consumption.

In summary, the majority of the existing work regarding optimization of the fuel consumption focused on the coordination of multiple vehicles in traffic. In this study, we focus on fuel consumption optimization from the perspective of the individual vehicle. This work discusses the issue of the driving strategy at the driver personal level to achieve the minimum use of fuel. We strongly believe that the issue is of interest to the general public.

We structure the document as follows. In Section 2, Research Methods, we present the research procedure, including the generation of the data related to the movement of vehicles and the computation of the fuel usage. In Section 3, Results and Discussion, we present the fuel usage for some cases of driving. Finally, we conclude the paper with Section 4, Conclusion, providing a brief but most important finding of the research.

2. **Research Methods.** To understand how the driving strategy affects fuel consumption, we establish a model of a platoon of 20 vehicles by using an agent-based approach. Each vehicle is considered as an agent with dynamic characteristics following the car-following model. Besides, we also develop a model involving only two vehicles. We use the latter model to simplify the problem. The fuel consumption analysis is more apparent when presented with the two-vehicle model.

As for the car-following model, we adopt the optimal velocity model or OVM, proposed by [10, 11, 12]. To express the OVM governing dynamics, we consider two vehicles moving on a close distance, see Figure 1. Vehicle $(n-1)$ is in the front followed by vehicle n.

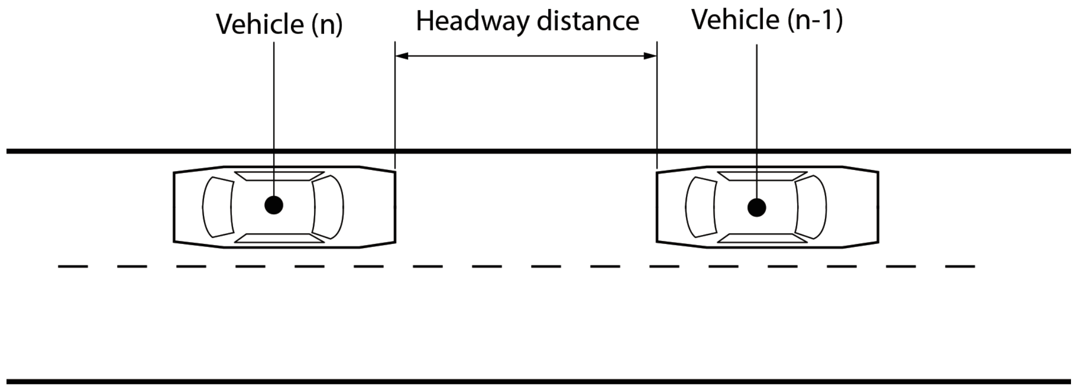

Figure 1. Two vehicles in a close distance for deriving the optimal velocity model. The leading vehicle has the index $(n-1)$ and the follower is n.

According to the OVM, the acceleration of vehicle n is governed by

$$\ddot{x}_n = a_n \left[V(\Delta x_n) - \dot{x}_n \right], \tag{1}$$

where $\ddot{x}_n$ is the time-varying acceleration of vehicle n, a_n is a driver sensitivity coefficient, $V(\Delta x_n)$ is an optimal velocity function that depends on the distance between the two vehicles or $\Delta x = x_{n-1} - x_n$, and $\dot{x}_n$ is the velocity of vehicle n at time t.

The expression suggests that the driver of vehicle n adjusts its acceleration depending on the relative distance and velocity with vehicle $(n-1)$, the leading one.

[13] proposed a revision to Equation (1) by taking account of the driver delay (t_d). The revision suggests that the acceleration of vehicle n does not depend on the relative distance at the time t but at the previous time, $t - t_d$. Their formula is written:

$$\ddot{x}_n + a_n \dot{x}_n = a_n V(\Delta x_n(t - t_d)). \tag{2}$$

[14] presented data suggesting the reaction time for driving is about 1 s. For a comparison, [15] found that the reaction time for selecting a button on a computer mouse is about 0.4 s. That value of the driving reaction time is widely accepted.

According to [11], an optimal velocity function should increase monotonically, and it should converge to an upper bound. The simplest function satisfying those conditions is

$$V(\Delta x) = \tanh(\Delta x - 2) + \tanh 2. \tag{3}$$

Meanwhile, the Newell's early proposal was

$$V(\Delta x) = v_0 \left(1 - \exp\left[-\frac{\Delta x - s_0}{v_0 T}\right]\right), \tag{4}$$

where s_0 is the jam distance, T is the headway time, and v_0 is the desired velocity. For Japanese highway, [16] proposed:

$$V(\Delta x) = 1.68 \cdot \tanh\left[0.086(\Delta x - 25)\right] + 0.913. \tag{5}$$

Finally, [17] proposed a general model of the optimal velocity function in the form:

$$V(\Delta x) = v_0 \left[\tanh\left(\frac{\Delta x - D}{B} - C_1\right) + C_2\right], \tag{6}$$

where D is the effective vehicle length, B is the braking distance, C_1 is the length constant, and C_2 is the dimensionless constant. The braking distance for safe driving for various vehicle velocities can be seen in Table 2 of [14].

The vehicle dynamics characteristics regulated by Equation (6) is the following. The vehicle starts braking at a distance of $D + C_1 \cdot B$ behind its leading vehicle. The vehicle free-flow velocity actually is $v_0 \cdot (1 + C_2)$. Therefore, to preserve the physical meaning of the parameter v_0, D, and B, it is convenient to set C_1 and C_2 to zero.

As mentioned above, in the current research, the platoon of vehicles is simulated by using an agent-based model (ABM). The model is shown in Figure 2. It is derived from the traffic model proposed by [18] and is revised such that each vehicle moves following the optimal velocity model described previously. Those 20 vehicles are assumed made of a similar type where each has a length of 5 meters. The platoon moves through a straight

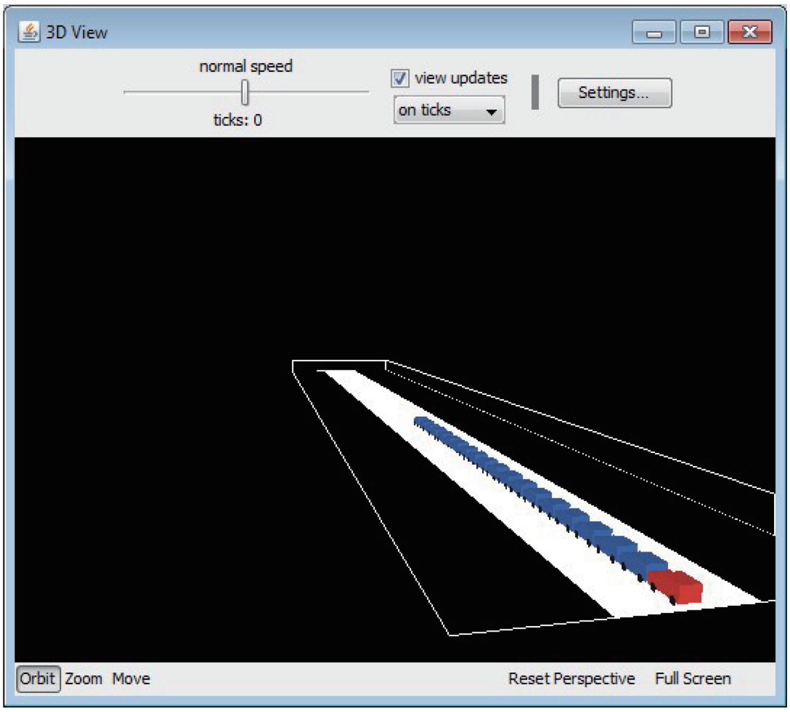

FIGURE 2. An agent-based model of a platoon of 20 vehicles

road segment of 10 km length. However, for the two-vehicle model, the road length is only 0.5 km.

The model is developed in NetLogo, an agent-based modeling software. Each vehicle is considered a turtle, the type of agent that can move in the model space, with certain initial positions depending on the case. For instance, in the case of two-vehicle dynamics, they are separated by an initial distance of 500 m. The leader vehicle position is fixed during the entire time of analysis. The vehicles move following the computation procedure described in Algorithm 1.

Algorithm 1: The procedure to compute the acceleration, velocity, and position of vehicles.

Data: $a_n = 1$; the initial velocity $\dot{x}_n = 0$; the initial position x_n; the time step Δt
while time $t <$ final time **do**

Prescribe the motion of the leader vehicle. The leader position is fixed in two-vehicle case.

Compute the acceleration of the follower vehicle:

$$\ddot{x}_n = a_n \left[V(\Delta x_n) - \dot{x}_n \right]$$

Compute the change of the velocity of the follower vehicle:

$$\Delta\dot{x}_n \leftarrow \ddot{x}_n \cdot \Delta t$$

Compute the change of the position of the follower vehicle:

$$\Delta\dot{x}_n \leftarrow \dot{x}_n \cdot \Delta t + 0.5 \cdot \ddot{x}_n \cdot (\Delta t)^2$$

Update the velocity of the follower vehicle:

$$\dot{x}_n \leftarrow \dot{x}_n + \Delta\dot{x}_n$$

Update the position of the follower vehicle:

$$x_n \leftarrow x_n + \Delta x_n$$

Compute the fuel consumption rate:

Equation (7)

Advance time:

$$t \leftarrow t + \Delta t$$

end

To achieve the objectives of the study, we require two models. The first is the model of vehicle dynamics. The second is the model of the fuel consumption. Above, we have discussed the first model. The second, the fuel consumption model, is discussed following.

As for the fuel consumption, many models have been proposed; see, for example, [19]. The best fuel model is given in Equation (7) where f is the fuel consumption rate. Based on the Federal Test Procedure (FTP), used by the Environmental Protection Agency (EPA), [19] found Model (7) correlating very well with Oak Ridge National Laboratory's data of [20] at the Pearson's coefficient of 0.995.

$$\begin{aligned}\log_e f = &-0.679439000 + 0.135273000 \cdot a + 0.015946000 \cdot a^2 - 0.001189000 \cdot a^3 \\ &+ 0.029665000 \cdot v - 0.000276000 \cdot v^2 + 0.000001487 \cdot v^3 \\ &+ 0.004808000 \cdot a \cdot v - 0.000020535 \cdot a \cdot v^2 + 5.5409285 \times 10^{-8} \cdot a \cdot v^3 \\ &+ 0.000083329 \cdot a^2 \cdot v + 0.000000937 \cdot a^2 \cdot v^2 - 2.479644000 \times 10^{-8} \cdot a^2 \cdot v^3 \\ &- 0.000061321 \cdot a^3 \cdot v + 0.000000304 \cdot a^3 \cdot v^2 - 4.467234000 \times 10^{-9} \cdot a^3 \cdot v^3 \quad (7)\end{aligned}$$

In Model (7), the symbol f denotes the fuel consumption in gallon/hour, a is the vehicle acceleration in ft/s^2, and v denotes the vehicle velocity in ft/s. To use the model, as our data are in m/s, m/s^2, and second, we use the conversion formulas of: 1 m/s^2 = 3.2808399 ft/s^2 for the acceleration data, 1 m/s = 3.28084 ft/s for the velocity data, and 1 gallon/hour = 0.0010515 L/s for the fuel consumption rate data.

3. **Results and Discussion.** We start the discussion with the simplest case. Two vehicles are placed on a straight road segment at two different locations separated by a distance of 500 m. Then, the follower vehicle, from its initial zero velocity condition, accelerates to approach the leading vehicle to reduce the headway distance between the two (see Figure 1). The leading vehicle is fixed in space. Furthermore, it is also assumed the follower vehicle moves according to the governing dynamics of the optimum velocity model as described in Section 2 with the values of the OVM's parameters as presented in Table 1. From the simulation, we observe the dynamics characteristics and the fuel consumption of the follower vehicle.

Table 1. The setting of the parameters of the optimal velocity model used in the current study

OVM parameters	Symbols	Values
The desired velocity (m/s)	v_0	*27.778
The effective vehicle length (m)	D	5
The braking distance (m)	B	110, 125, 150
The length constant	C_1	0
The dimensionless constant	C_2	0

*Equivalent to 100 km/h

From the fuel consumption model as described by Equation (7), we understand that the consumption depends strongly and intricately on the vehicle acceleration and velocity. In the context of the optimal velocity model, those characteristics are affected by the braking distance parameter. Thus, we study the fuel consumption for three realistic values of the braking distance at the desired velocity. We set the parameter to vary as 110 m, 125 m, and 150 m. We note that [14] reported, for a vehicle moving at 100 km/h, the safe braking distance is 110 m, taking account of the driver reaction time.

We simulate the event and compute the acceleration, velocity, position, and fuel consumption of the follower vehicle. The results are presented in Figure 3. We observe the following phenomena from the case.

The follower vehicle undergoes a very high acceleration to reach the desired velocity of 100 km/h or about 27.778 m/s. The computation shows the acceleration reaches a maximum value of about 30 m/s^2 for the three cases of the braking distance.

When it reaches the desired velocity, the vehicle maintains its movement at nearly zero acceleration. When the distance to the leading vehicle is slightly higher than the braking distance, the follower vehicle begins decelerating until it stops behind the leading vehicle at the headway of 5 m, the effective vehicle length.

Generally speaking, for the three values of the braking distance, the acceleration, velocity, and position histories are nearly identical. However, significant variations are observed on the fuel consumption. Mostly, high fuel consumption occurs at two points in time. The first point is near the starting time when the vehicle nearly reaches its desired/maximum velocity, where the vehicle acceleration is low. At this point, the braking distance does not affect the movement and does not affect fuel consumption.

As for the second point, the fuel consumption is also high during the deceleration. On this condition, the vehicle with the shortest braking distance, 110 m, consumes much more fuel. In the term of the rate of the fuel consumption, at the time instant of 18 s, the 110-m braking-distance vehicle requires 13× more fuel than the vehicle with 150-m braking distance, and 4× more than that of 125-m braking distance.

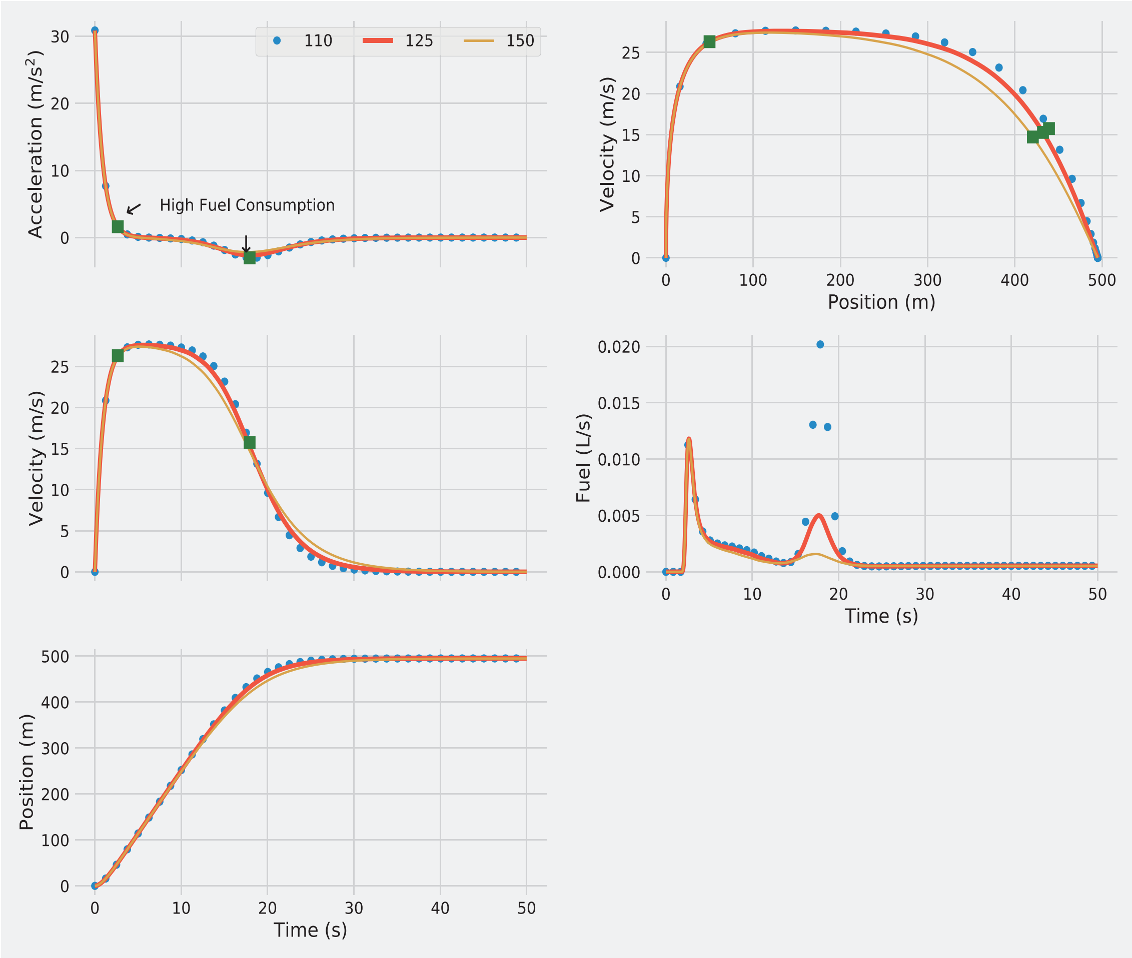

FIGURE 3. The dynamics characteristics – acceleration, velocity, and position – and the fuel consumption of a vehicle traveling according to the optimum velocity model. The boxes denote the points where the fuel consumption is high.

The amount of fuel used by the follower vehicle for traveling the 500-m distance is 0.100 L, 0.066 L, and 0.053 L for the braking distance 110 m, 125 m, and 150 m, respectively. In other words, the 110-m braking distance vehicle utilizes 50% more fuel than that of 125-m braking distance and 90% more fuel than that of 150-m braking distance. The small change in vehicle acceleration at a high velocity affects the use of fuel significantly.

Next, we discuss another simple case. That is the case of a single vehicle moving at a constant speed across a 10-km straight road. We understand that the problem is straightforward and can be quickly and accurately computed analytically for the vehicle position, velocity, and acceleration. However, we simulate and solve the problem numerically by using agent-based modeling, and we validate the model by comparing its results to the analytical solutions. We show in Figure 4 the duration and fuel consumption required by the agent (vehicle) to cross the 10-km-long road segment. The most efficient fuel consumption is obtained at the 60-km-per-hour speed. We also validate that the ABM model is entirely accurate.

The last case is the case of 20 vehicles moving in a platoon. The interactions of the vehicles are assumed to follow the optimal velocity model. According to the model, the interaction is strongly affected by the desired vehicle velocity and braking distance. Thus, we analyze the vehicle interaction for the braking distance of 5 m, 10 m, ..., 25 m. we also vary the desired vehicle velocity as 10 km/h, 20 km/h, ..., 100 km/h. The platoon is moved within a closed-loop track with a circumferential length of 10 km.

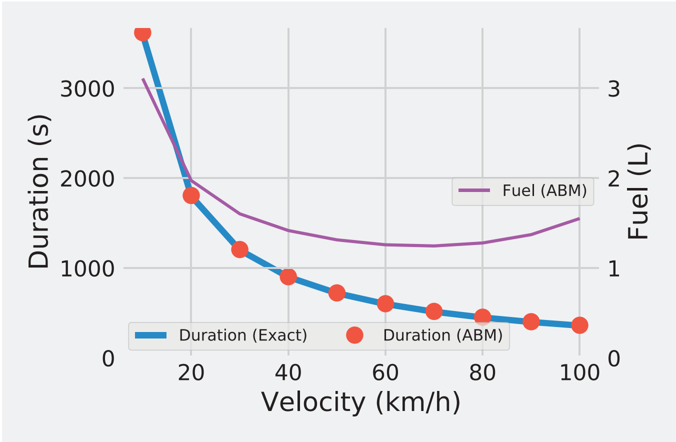

Figure 4. The duration and fuel consumption for a vehicle to cross a 10-km length road segment

The results are depicted in Figure 5, and the data and their statistics are shown in Table 2. Generally, the fuel consumption drops by increasing the desired velocity until a certain speed, but then, the fuel consumption increases dramatically with speed. For instance, for the case of 25 m braking distance, the fuel consumption drops from about 14 L at the desired speed of 10 km/h to about 3 L at 80 km/h. Then, the fuel consumption quickly increases to a level of 6 L at the desired speed of 100 km/h.

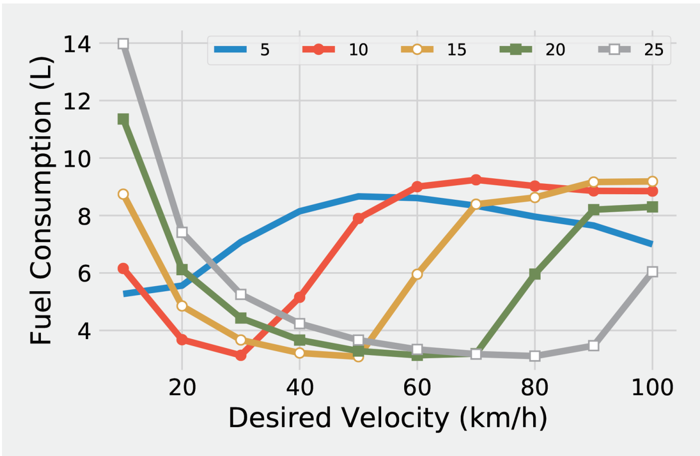

Figure 5. The fuel consumption of a vehicle within a platoon of 20 vehicles to cross a 10-km length road segment for various desired velocity and the braking distances of 5 m, 10 m, ..., 25 m

Now, we bring our focus to the points on the curves associated with the minimum fuel consumption for the studied braking distances. The points are isolated and presented in Figure 6. The figure shows a set of combinations of the braking distance and the desired velocity that lead to the minimum fuel consumption. The results suggest that the minimum fuel consumption can be obtained by various combination of the braking distance and desired speed. It can be obtained with the combination of both parameters at: (30 km/h, 10 m), (50 km/h, 15 m), (60 km/h, 20 m), and (80 km/h, 25 m). On those settings, the amount of fuel to cross the 10-km distance is approximately the same the average of 3.116 L and a minimum standard deviation of 0.024 L. The relation between the two driving parameters is also linear with the determination coefficient of R^2 of 0.985, as depicted in Figure 6. The linear model we fit the data suggests that for every 10-km-per-hour increment in the vehicle speed, the braking distance should be increased by 3 m to maintain a minimum fuel consumption.

TABLE 2. The fuel consumption of a vehicle moving within a platoon of 20 vehicles across a 10-km road length for various desired velocity and the braking distance of 5 m, 10 m, ..., 25 m

Desired velocity (km/h)	Braking distance (m)				
	5	10	15	20	25
10	5.270	6.157	8.743	11.357	13.980
20	5.560	3.679	4.852	6.117	7.415
30	7.080	3.134	3.668	4.431	5.255
40	8.148	5.154	3.215	3.666	4.238
50	8.666	7.897	3.085	3.283	3.665
60	8.608	9.003	5.956	3.136	3.339
70	8.340	9.242	8.393	3.193	3.176
80	7.959	9.024	8.627	5.962	3.108
90	7.651	8.857	9.165	8.202	3.470
100	6.998	8.849	9.186	8.301	6.042
Max	8.666	9.242	9.186	11.357	13.980
Min	5.270	3.134	3.085	3.136	3.108
Ratio	1.644	2.949	2.978	3.621	4.498
Mean	7.207	7.363	7.263	7.059	7.154
Standard deviation	1.357	2.418	3.561	5.039	6.716

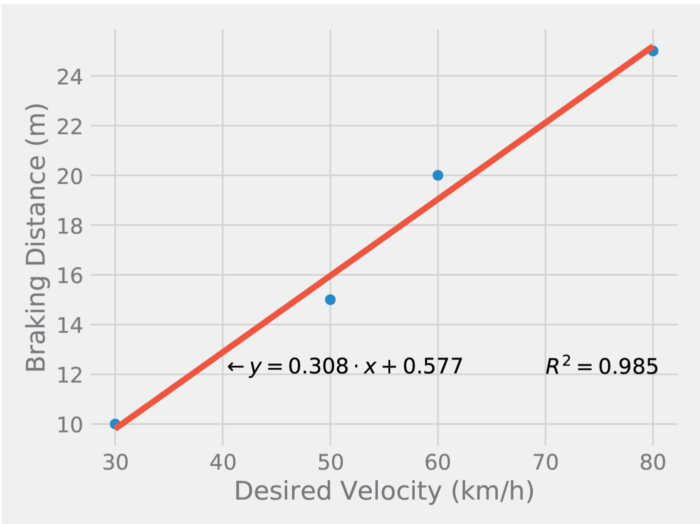

FIGURE 6. The relationship between the desired velocity and the braking distance at the condition of the most optimum fuel usage for the vehicle moving in the platoon

Figure 5 also depicts one more interesting phenomenon. That is the event of a sudden and significant increase in fuel consumption after the point of minimum fuel consumption. This event is not only unique to certain braking distance but occurs rather uniformly across all cases. The data suggest that after the minimum point, the consumption of the fuel increases by 0.25 L/(km/h), a massive increase in fuel consumption.

4. **Conclusion.** Driving strategy to achieve efficient usage of fuel has been the topic of the discussion of many research articles. Recently, interest in the topic is growing at a fast pace. Many ideas have been proposed, spanning from vehicle platooning, up to the driving in fully automatic and coordinate traffic. This research work takes a slightly different approach. It looks the fuel-efficient driving strategy from a personal perspective.

With such a view, we expect the results will be of interest of the more substantial audience. The main result shows that taking strong braking on a high traveling speed leads to a massive increase in fuel consumption. To maintain the efficient usage, adjustment between the desired traveling speed and the braking distance should be made with great care.

As for future research, we recommend taking account of other models of the car following, for example, the intelligent driver model or IDM. By using the model, more aspects of driving, and their effects on fuel consumption can be studied, leading to a better understanding of the personal level driving strategy.

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