The Most Optimum Speed Range for Energy Conservation and Emission Reduction on Expressways for Cars

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Abstract: As one of the most important topics of the times, the concept of energy conservation and emission reduction is also of great significance in the field of traffic and transportation. When small cars travel on the expressways, there exists a clear correlation between travel speed and both the fuel consumption as well as emission ratio of CO₂. According to the law of conservation of matter, with the same fuel consumption, a high emission ratio of CO₂ reflects both an efficient use of fuel and a decrease in the emission of harmful gases; and the speed range that offers the most optimum energy conservation and emission reduction is the objective of this study. A data analysis on three groups of experimental automobiles was carried out to express their correlation into a detailed function expression using the function fitting method. In accordance with the function expression, the most optimum speed range for energy conservation and emission reduction can be obtained by making reference to the maximum integral area. In this study, data from Toyota automobiles were taken as samples to determine the most optimum speed range. According to the results, the most optimum speed range for Toyota is from 65.8 km/h to 85.8 km/h, which indicated that for similar car models, the best performance in fuel utilization and emission reduction can be acquired if they conform to the above speed range when traveling on expressways.

1. Introduction
With the constant development in economy, there is more and more need for transportation. The total mileage on expressways is increasing year by year. Traffic and transportation is one of the most energy-consuming industries in China. The massive amount of expressways being constructed has also boosted the demand for transportation. However, this has also led to a high consumption of fuel and an even higher emission of CO₂. This has aroused a widespread social concern not only because of its negative impact on sustainable development, but also the severity of the damage it would cause to human health and ecological environment.

Other than implementing exhaust gas treatment and conducting research for the development in green automobiles [1], controlling automobiles’ operational states on the expressways can contribute significantly to solving the problems related to energy conservation and emission reduction for automobiles. A study on the operational states of automobiles in traffic at expressways toll stations carried out by Cui Hongjun et al has shown that a sharp increase in fuel consumption and gas emission could be caused by low travel speed, idle speeds, or shut down [2]. Based on the research by Tan Yan-ni [3], it was found that both fuel consumption and exhaust gas emission are closely related to the travelling speed of automobiles; when travelling at speeds of 50 km/h to 90 km/h, a low fuel consumption and emission could be attained, whereas a sharp increase in fuel consumption and emission would occur at speeds out of that range. A research on automobiles at low speeds by Yao Zhiliang [4] showed that there
is a clear correlation between pollutant emission and speed. Engines performed better in terms of achieving the lowest emission factors of gaseous pollutants when agricultural vehicles traveled at speeds of 40 km/h to 50 km/h. Through a vector regression model, Bin Xu \[5\] discovered that the efficiency of fuel utilization offers a significant influence on energy conservation and emission reduction through an analysis on the influencing factors of the changes in carbon emission in transportation. When automobiles travel on expressways, several factors may influence carbon emissions, such as road alignment, road condition, weather, and drivers’ mental states.

In general, the impacts can be reflected through the changes in the automobile’s travel speed. To sum up, a study on the relationship between speed and both the fuel consumption as well as the exhaust gas emission could be conducted to determine a reasonable speed range. Traveling within this speed range ensures the efficiency of fuel combustion and a reduction of harmful gases emission as much as possible. This study can hence be considered to be of great practical significance for energy conservation and emission reduction of automobiles.

2. Theoretical Basis

2.1. The main harms of carbon-containing exhausts

Automobiles that travel on expressways mainly include cars and trucks, which are fueled by gasoline and diesel oil respectively. However, their exhaust gases are totally different in terms of type and the proportion of pollutants. The main components of these pollutants are depicted as follows \[1\].

![Figure 1. Type of vehicle exhaust emission](image-url)

According to Figure 1, the main pollutants that are related to the carbon emissions of automobiles traveling on expressways include hydrocarbons, CO and CO\(_2\). CO is a colorless, tasteless, and asphyxiating toxic gas with low solubility. Hydrocarbons, on the other hand, is notorious for hampering the growth of trees on the roadsides. Both pollutants are products of incomplete fuel combustions. Prolonged inhalation can incur a serious damage to health. Unlike the above pollutants, as a product of a complete fuel combustion, CO\(_2\) is non-toxic, but is still one of the main causes of the greenhouse effect. Statistically speaking, carbon emission levels of cars is much higher than that of trucks. It is due to this reason that cars were selected as the main experimental target for this study.

2.2. The principles of energy conservation and emission reduction

In contrast to CO\(_2\), CO and hydrocarbons, which are products of the exhaust gases from automobiles, have a much more serious damage to the environment and people’s life. It is rather difficult to absorb or convert both these gases. On the contrary, CO\(_2\) is soluble in water, and is one of the main components of photosynthesis in plants regardless of its harm. With the growing emphasis of greening on expressways, CO\(_2\) emitted by automobiles can be absorbed much effectively to maintain the stable content of CO\(_2\) in the air, which is a simple method to reduce its negative impact on the environment.

According to the law of conservation of matter, when gasoline is burnt, the carbon content in exhaust gases equals the total carbon content in fuel. Therefore, the higher is the emission ratio of CO\(_2\) in the
exhaust gas, the more complete is the combustion and the more effective is the fuel utilization. This means that the emission of CO, hydrocarbons, and other carbon-containing pollutants are much lower, and that lesser damage is incurred to the environment, which contributes greatly to energy conservation and emission reduction.

Based on the abovementioned principle, a research on the relationship between fuel consumption at different speeds and emission ratios of CO\textsubscript{2} will be carried out.

3. Experiments and Results

3.1. Experimental scheme

The influence of different types of automobiles on the test results has been excluded in the study on the relation between the traveling speed and both the fuel consumption and CO\textsubscript{2} emission. A random sampling of automobiles on expressways has been conducted and finally, there are three types of automobiles selected for the test out of a group of sample automobiles and they are Volkswagen, Ford, and Toyota respectively. Tests on those three types of automobiles were carried out when they were traveling on the expressway to collect data about their fuel consumption and emission ratio of CO\textsubscript{2} at instantaneous speed. To exclude the influence of other factors, tests on those three types should be carried out under the same conditions. In this study, the testing conditions are sunny, no wind and a flat road with little interference. Moreover, automobiles to be tested should be filled up with the same fuel oil. Each tested automobile is followed by researchers to get useful information. Data about fuel consumption can be got directly from the fuel gauge while the instantaneous value of emission ratio of CO\textsubscript{2} is available based on Kane Auto5-1, a tester for CO\textsubscript{2} emission. Average of collecting data from several tests on each automobile to be tested should be picked to avoid contingencies in the test. The main parameters of each automobile to be tested can be referred from in Table 1.

| brand    | Engine model | power (kw) | displacement (L) |
|----------|--------------|------------|-----------------|
| Volkswagen | LangYi        | 89.4       | 2.0             |
| Ford     | Carnival      | 76.8       | 1.5             |
| Toyata   | Prado         | 179        | 4.0             |

3.2. The relationship between speed and fuel consumption

Fuel consumption of an automobile is not only related to its weight but also changes with its speed. Test on fuel consumption at a constant speed aims to determine the total fuel consumption of the automobile when it runs a certain distance (500 meters) at a specifically constant speed. In order to avoid interference, all fuel-consuming configurations, such as air-conditioner, powered windows and broadcasting should be shut down during the testing procedures. Testing range for speed is from 40 km/h to 120km/h, in which there is a measurement every 10km/h to ensure all general speed on expressway included. It is noted that all measurements should be completed in a still day on an automobile traveling on a flat road at constant speed, whose aim is to conclude the law between speed and fuel consumption. Fuel consumption in detail for different type automobiles can be referred in Table 2 according to the test results and line chart is shown in Figure 2.

| Speed (km/h) | Volkswagen | Ford | Toyata |
|--------------|------------|------|--------|
| 40           | 9.0        | 7.5  | 13.0   |
| 50           | 8.3        | 6.4  | 12.5   |
| 60           | 7.4        | 6.2  | 11.2   |
| 70           | 7.0        | 5.6  | 10.6   |
Figure 2. Relationship between speed and fuel consumption

According to Table 2 and Figure 2, it is found that there is a certain relation between fuel consumption for 100km and the constant speed. We can see that for Toyota, fuel consumption will decrease with the speed increasing from a speed of 40km/h and fuel consumption for 100km gets it minimum when its travel speed is 90km/h. However, fuel consumption for 100km will increase in a large range with the increasing speed subsequently. It is similar to Volkswagen and Ford, in which fuel consumption of Volkswagen gets its minimum when speed is 80km/h while Ford at 70km/h. Subsequently, the speed of those two types of automobiles will increase and both of their increasing ranges are slightly smaller than those who of Toyota.

In accordance with the curve of constant speed fuel consumption, there is an economic speed for each automobile, which means the most fuel-efficient speed for them. Different types of automobiles own different economic speeds. However, all their fuel consumption will increase when they travel at a speed higher or lower than their economic one. A low driving speed will cause a low moving speed of the piston, which would lead to incomplete combustion while an increase in intake speed would lead to an increase in both intake resistance and wind resistance at a high driving speed, all of which will cause more fuel consumption definitely [6].

3.3. The relationship between speed and emission ratio of CO2

Under the same testing conditions, several tests are carried out to conclude fuel consumption and emission content of CO2 by Kane Auto5-1. Inaccurate data of samples have been excluded. The final testing result can be got based on the average of emission ratio of CO2 at the same instantaneous speed. Emission ratio of CO2 of different automobiles at different speeds can be found in Table 3 and line chart is shown in Figure 3.

| Speed (km/h) | Volkswagen | Ford | Toyota |
|--------------|------------|------|--------|
| 40           | 14.32      | 14.57| 14.89  |
| 50           | 14.67      | 15.11| 15.25  |
| 60           | 15.21      | 15.29| 15.61  |
| 70           | 15.38      | 15.55| 15.72  |
| 80           | 15.18      | 15.43| 15.93  |
According to Table 3 and Figure 3, we can see that for both Volkswagen and Ford, their emission ratio of CO₂ gets their maximum when their instantaneous speed is 70km/h. However, the emission ratio of CO₂ will decrease in a small range as the instantaneous speed increases subsequently. When the instantaneous speed is lower than 70km/h, the emission ratio of CO₂ will decrease in a large range with a decreasing speed. For Toyota, its emission ratio of CO₂ gets its maximum when its instantaneous speed is 80km/h. As the instantaneous speed increases, its emission ratio of CO₂ will decrease with a slightly larger range than that of both Volkswagen and Ford. Moreover, when its instantaneous speed is lower than 80km/h, the emission ratio of CO₂ will decrease in a large range with a decreasing speed.

To sum up, for those three types of automobiles, there is a slight difference in the relationship between their speed and fuel consumption and the peak of emission ratio of CO₂. In general, it can be concluded that there is a correlation between speed and fuel consumption and emission ratio CO₂.

4. The most optimum speed range

According to a study on the relation between speed and fuel consumption and emission ratio of CO₂, we have known that there are some changes in fuel consumption and emission ratio of CO₂ respectively as speed changes. Therefore, we can determine the most optimum speed range for energy conservation and emission reduction based on the study results. In accordance with the most optimum speed range, it can be seen that fuel consumption is low in a complete combustion, which means that a high emission ratio of CO₂ is available but it definitely achieves energy conservation and emission reduction at the same time. It can reduce the damages of exhaust gases on the environment and introduce some advice for drivers on the expressway.

In the next sections, Toyota will be selected as a sample to determine the most optimum speed range for energy conservation and emission reduction.

4.1. Normalization processing of data

Based on the standardization of data, data should be scaled and unit limitation on them also should be removed to be converted into dimensionless pure values, which is convenient to carry out a comparison among or analysis on those indicators with different units or magnitude orders. The most typical one is the normalization processing of data, that is, all data are mapped uniformly to the range [0, 1].

In this study, Min-max standardization is adopted and it is also can be called deviation standardization. It is a kind of linear transformation of the original data to make the data fall into the range [0, 1]. The transform function can be referred in (1) [7].

\[
\text{Transform function} = \frac{x - \text{min}(x)}{\text{max}(x) - \text{min}(x)}
\]
\[ x^* = \frac{x - \min}{\max - \min} \]  

In the formula, \( x \) represents the sample data while \( \max \) and \( \min \) represents the maximum and minimum of the sample data respectively. Data about the tested Volkswagen are dealt with normalization processing. Results are shown in Table 4.

| Speed (km/h) | Min-max standardization Fuel consumption | CO₂ emission ratio |
|--------------|--------------------------------------|-------------------|
| 40           | 0.862068966                          | 0.330188679       |
| 50           | 0.620689655                          | 0.839622642       |
| 60           | 0.310344828                          | 1                 |
| 70           | 0.172413793                          | 0.811320755       |
| 80           | 0.24137931                           | 0.622641509       |
| 90           | 0.310344828                          | 0.566037736       |
| 100          | 0.724137931                          | 0.528301887       |
| 110          | 1                                   | 0.339622642       |

4.2. Determine the most optimum speed range

To take all factors into account, such as speed limitation on expressway and driving habits of different drivers [8], a range with a length of 20km/h is selected for the most optimum speed range. According to the discussion in the sections above, a determination of the most optimum speed range can be calculated through the maximum of the area enclosed by those two curves above and two straight lines, both of which are parallel to y-axis with a distance of 20km/h. Combining to the data of Table 3.1, it can be referred to in Figure 4.

Figure 4. Schematic diagram of area calculation

Seen from the figures, the maximum of shadow area is corresponding to the speed range for the most optimum CO₂ emission range. Calculating steps can be referred to as follows to determine this range.

i. To fit the relation between the standardized fuel consumption and the standardized emission ratio of CO₂ through their different functional relationship to determine the optimal function equation for fitting;

ii. To calculate the intersections of two curves of the standardized fuel consumption and the standardized emission ratio of CO₂ according to two equations in step i.

iii. To determine a range with a width of 20 within the range between those two intersections, in which a maximum area can be enclosed with those two fitting curves above. It can be calculated in
steps as follows.

Standardized fuel consumption for 100km and observation value of speed should be fitted with different functional models of the linear function, quadratic function, cubic function, logarithmic function and exponential function respectively. Sum of models and assessment values of parameters can be referred in Table 5 and model fitting curve is shown in Figure 5.

| Function       | Parameter estimation | R²   |
|----------------|----------------------|------|
| linear         | 0.00155 0.347 - - 0.015 |
| quadratic      | 0.00054 -0.084 3.421 - 0.943 |
| cubic          | 4.9E-07 0.00042 -0.075 3.2 0.963 |
| logarithmic    | -0.0210 -3.1E-07 - - 0 |
| exponential    | 0.2401 0.00803 - - 0.037 |

![Figure 5. Schematic diagram of curve fitting](image)

According to fitting results of each model shown in Table 5, speed and standardized fuel consumption for 100km should be fitted with a model with a maximum value of R². It is found that the maximum fitting degree is a cubic curve. Based on the calculation on parameters in Table 5, its formula can be represented as the formula in (2).

\[
y = 3.216 - 0.075x + 4.18 \times 10^{-4}x + 4.934 \times 10^{-7}x^3
\]

(2)

y—standardized fuel consumption for 100km (L/100km);

x—speed (km/h).

Simultaneously, speed should be fitted with the observation value of the standardized emission ratio of CO₂. Sum of models and assessment values of parameters can be referred in Table 6 and model fitting curve is shown in Figure 6.

| Function       | Parameter estimation | R²   |
|----------------|----------------------|------|
| linear         | 0.00171 0.423 0.023 - 0.02 |
| quadratic      | -0.0004 0.0701 -2.03 0.770 0.88 |
| cubic          | 8.69E-06 0.0025 0.227 -5.66 0.91 |
| logarithmic    | 0.24161 0.135 0.085 - 0 |
| exponential    | 0.4699 0.002 0.017 - 0.27 |
According to fitting results of each model shown in Table 6, speed and the standardized emission ratio of CO₂ should be fitted with a model with a maximum value of R². It is found that the maximum fitting degree is a cubic curve (R² = 0.913), which can be expressed based on the formula in (3).

\[
y = -5.659 + 0.227x - 2.5 \times 10^3 x^2 + 0.69 \times 10^6 x^3
\]  

(3)

- y——standardized emission ratio of CO₂ (%);
- x——speed (km/h).

Intersections can be calculated based on formula (2) and formula (3). Dichotomy is applied to solving this question and calculating steps can be seen as follows.

i. To determine the range including the intersection roughly, such as [40, 80], and then to initialize the calculation in a₁ = 40 while a₂ = 80.

ii. To judge the value based on the formula a₂ - a₁ is lower than the precision (0.01) or not. If, continue in step iv, else in step iii.

iii. To set \( x = (a₁ + a₂)/2 \) and to calculate the value of \( y₁(x) \) and \( y₂(x) \), both of which are the fitting value between the standardized fuel consumption and the standardized emission ratio of CO₂ according to the calculating steps above. If \( y₁(x) > y₂(x) \), set a₁ = x to renew the value of a₁ and return to step iv; else, assume a₂ = x to renew the value of a₂ and return to step ii.

iv. Finally, the abscissa of the intersection with the lower speed can be got based on the formula \( (a₁ + a₂)/2 \).

According to the steps above, the coordinates of the two intersections are (51.1, 0.522) and (105.4, 0.492) respectively. The maximum area is included in the range [51.1, 105.4]. To assume that fitting function of the standardized fuel consumption and the standardized emission ratio of CO₂ were \( f₁(x) \) and \( f₂(x) \) respectively, then find maximum of integral to work out the answer according to the formula in (4).

\[
z = \int^{x=105.4}_{x=51.1} (f₂(t) - f₁(t)) \, dt
\]  

(4)

Differential element method is applied to solving this question. Beginning from the abscissa of the left intersection, each area enclosed by range with a length of 20 and curves should be calculated based on a step size of 0.1. This calculation will not stop until it comes to the right intersection, in which area of each differential element should be calculated with a width of 0.01. Finally, the total area of this range can be got through accumulation. In accordance with steps above, areas of 344 ranges from [51.1, 71.1], [51.2, 71.2]…… to [85.4, 105.4] can be calculated. The range with the maximum area is the most optimum speed range for carbon emission. Areas of some ranges have been calculated and shown in Table 7.
Table 7. Partial results of range calculation

| Space range | Areo     | Space range | Areo     |
|-------------|----------|-------------|----------|
| [62.3,82.3] | 14.095   | [65.8,85.8] | 14.36    |
| [62.4,82.4] | 14.11    | [65.9,85.9] | 14.36    |
| [62.5,82.5] | 14.125   | [66.8,86]  | 14.359   |
| [62.6,82.6] | 14.139   | [66.1,86.1] | 14.358   |
| [62.7,82.7] | 14.153   | [66.2,86.2] | 14.356   |
| [62.8,82.8] | 14.166   | [68.7,88.7] | 14.182   |
| [62.9,82.9] | 14.179   | [68.8,88.8] | 14.169   |
| [63,83]     | 14.192   | [68.9,88.9] | 14.157   |
| [65.5,85.5] | 14.358   | [69.89]    | 14.144   |
| [65.6,85.6] | 14.359   | [69.1,89.1] | 14.13    |
| [65.7,85.7] | 14.36    | [69.2,89.2] | 14.116   |

According to the results in table 7, the maximum area is 14.36, the corresponding interval is [65.8,85.8], as shown in Figure 7.

![Figure 7. Optimal range for car of Volkswagen](image)

Based on the results, Volkswagen can run at speed included within this range with low fuel consumption and the minimum content pollutant gases. Simultaneously, the most optimum speed range of other types automobiles for energy conservation and emission reduction are available according to the steps mentioned above and it would not be given in detail anymore.

5. Conclusions

Based on repeated studies on low carbon traffic on expressways by different researchers home and abroad, a research on the relation between speed on expressway and energy conservation and emission reduction had been carried out through different practical observation and tests and some conclusions can be referred as follows.

i. By instructing the experiment cars to travel at different but constant speeds, the changes of fuel consumption for 100 km can be concluded through data recording and calculation. A general law for those changes can then be obtained by comparing the three types of automobiles.

ii. For an automobile, its fuel consumption for 100km and emission ratio of CO₂ should be standardized with its speed. Then, a comparison among them is carried out in the same coordinate. Based on the law of conservation of matter, the concept of the most optimum speed range for energy conservation and emission reduction can then be proposed after an analysis has been made on the components of carbon-containing exhaust gases. And some formulas are also put up to calculate some speed ranges, which is economic for energy conservation.

To determine the most optimum speed range for carbon emission has offered some standard and principles to control the traveling speed on expressways for traffic managers. Subsequently, some
economic measurements can be carried out to offer travel methods and protect the environment and human’s health at the same time through reduction in the emission of harmful gases. However, study on the relation between speed and fuel consumption for 100km and emission ratio of CO₂ is carried out under some experimental conditions. Actually, other influential factors, such as bad weather and different roads, would have an impact on the determination. To sum up, it is necessary to carry out further study on the changing trends in detail.

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