Impacts of road grade on fuel consumption of light vehicles by use of Google Earth DEM

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Abstract—**Recently, more and more vehicles are running on the road, which causes fuel consumption and environmental pollution problems. As a significant factor to the fuel consumption, road grade is often neglected in the vehicle energy consumption model and the decision of optimal path of the vehicle navigation system because of the difficulty of its collection and measurements. This work demonstrates the impact of road grade on the fuel consumption under different speeds and the change of vehicle fuel consumption due to the change of road gradient based on light vehicles' driving data in Beijing, elevation data available from the Google Earth DEM. In addition, we characterize the influence of driving styles on the fuel consumption before and on the slope. The results indicate that the effects of road grade should not be excluded from vehicle energy consumed evaluations and path choosing, i.e., "eco-routing".**

Keywords-Road Grade; Google Earth DEM; Vehicle Fuel Consumption; eco-routing

I. INTRODUCTION[1]

Due to the growing volume of vehicles in China, the transportation industry has become one of the major industries of China's energy output, which caused the energy problems and environmental pollution problems. According to the data, by the end of 2013, the volume of vehicles in China has reached 223.828 million [1], maintaining the superpower positon for consecutive four years all over the world. The emission pollutants of vehicle totaled 46.121 million tons, in which hydrocarbons (HC) 4.382 million tons, carbon monoxide (CO) 34.712 million tons, this not only causes the haze and photochemical pollution, but also poses a serious threat to the health of residents. Therefore, how to reduce the energy consumption, lessen emissions at source, becomes a pressing issue before the world.

In order to quantify the vehicle energy consumption, experts and scholars in related fields have done a lot of research about fuel consumption model, for example, CMEM [2], developed by the University of California-Riverside, VT-Micro [3], proposed by Rakha et al. However, limited by the difficulty of acquisition technology and equipment of road elevation, most energy models (for example, VT-Micro and EMIT [4,5]) don't take road grade into consideration.

Research[6.8] shows that the road grade does have a great influence on vehicle exhaust emissions and energy consumption. For uphill, influenced by vehicle's own gravity and the road friction, motor vehicle drivers often need to gas to maintain a constant speed, which leads to an increase of fuel consumption, while for downhill, the inertia will push it, which means driver needn't do anything except brake when it runs too much fast, and in this case, it consumes little. By using the PAMVEC energy model, Melissa[7] compared the fuel consumption when taking road grade into consideration with the case without road grade, and chose the path between an O-D (Origin-Destination) which consumed less under the two circumstances. As a result, it indicates that we may probably make a wrong choice without considering road grade. Additionally, small-scale of test vehicles leads to a higher deviation of fuel prediction in existing studies.

The remainder of this paper is organized as follows. Section 2 gives a comprehensive review of the method how to calculate the road grade with Google Earth DEM. Section 3 describes the data source we use and discusses the impact of the engine displacement on the fuel consumption. Section 4 analyzes the relationship between the road grade and fuel consumption of vehicles, discusses the variation of fuel consumption when the speed changes both on the slope and flat road, the change in vehicle fuel consumption due to the inclusion of road grade, the impact of driving styles on fuel consumption before and during uphill. Conclusions are drawn in Section 6.

II. EVALUATION OF ROAD GRADE

Inspired by Ren et al, we developed an intuitive toolset to extract road network elevation data from the Digital Elevation Model (DEM) [9] database included in Google Earth [10] which is mapped by NASA and other US agencies with precision satellite imagery and remote sensing. Data get from DEM have a small deviation less than 3m in Beijing area, and as shown in Fig.1, the topography is roughly consistent with the extracted data.

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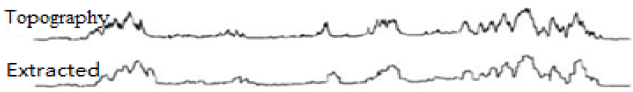

Figure 1. Comparison of the topography and data extracted from DEM

We can get the elevation data through the toolset as follows: 1) Load the vector map of Beijing road network. 2) Select the road links according to the link ID. 3) Generate the Key Markup Language file which can be identified by Google Earth. 4) Call the Google Earth DEM to get the path information from the file in step 3 and extract the elevation data at intervals of 5m corresponding to the links from the vector map. According to the elevation data we can calculate the road grade like this: Assuming the gradient within 5m is constant, the road grade between two nodes can be calculated by dividing the elevation gap of the two nodes by the interval. For a link with a length of *l*m which is divided into n sections shown in Fig.2, we always ignore the nodes between the start-node and end-node and define the grade of the link as the grade of the start-node and the end-node. The precision of calculated road grade angle can be more than 90% according to our sampling test.

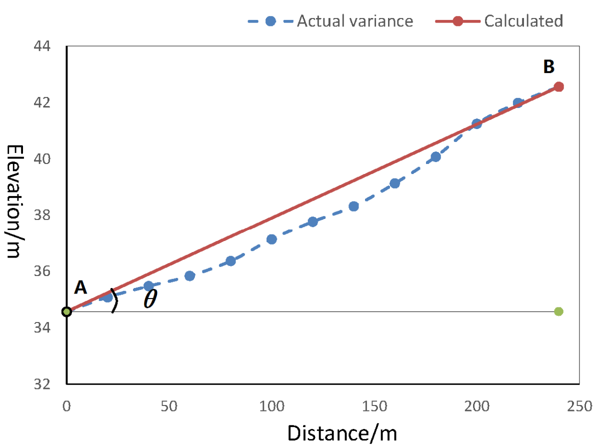

Figure 2. Grade of a link

For each link, we define it as:

$$C = (cid, d, P_1, \ldots, P_n)$$

Where cid is the link number in the vector map, d is the length of the link, $P_1 \ldots P_n$ means the nodes after division. The grade angle can be calculated as:

$$\tan\theta = (E_n - E_1)/l$$

Where E_n is the elevation of B and E_1 is the elevation of A, l is the horizontal distance of A and B. The precision of calculated road grade angle can be more than 90% according to our sampling test.

III. DATASET DESCRIPTION

A. *Data collected by CAN*

Experimental data for this paper comes from 12 million records driving data collected by 600 volunteer light vehicles in Beijing, which cover almost the road network in Beijing. The data was collected by Controller Area Network (CAN)-Bus installed inside the vehicle per second, including vehicle ID, instant speed, acquisition time (accurate to second), position (latitude and longitude), distance in a second and instant fuel consumption. CAN-Bus refers to the communication network used to get the vehicle's driving parameters[11]. It is shown in Fig.3 how the CAN bus works.

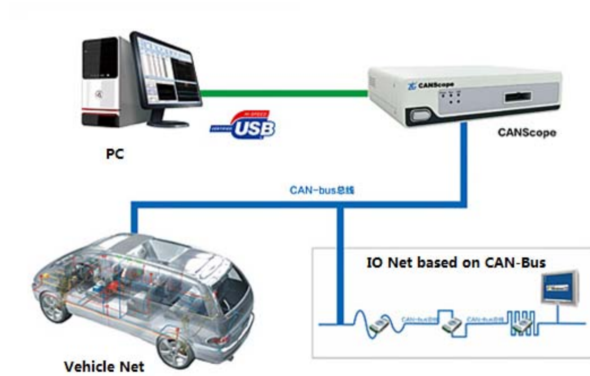

Figure 3. Schematic diagram of CAN-bus

B. *Other data*

Other data includes vehicle specification data (vehicle type, vehicle weight, displacement, etc.).

Differences in the engine displacement often lead to the different fuel consumption when vehicles run in the same pattern. However, the engine displacement of most vehicles in China are among the 5 categories: 1.5L, 1.6L, 2.0L, 2.3L, 2.5L, 3.0L, in which 1.6L, 2.0L and 2.5L occupy a large proportion. From the data 600 vehicles get we can get the relationship between the driving pattern and the fuel consumption in reference of the engine displacement and the speed.

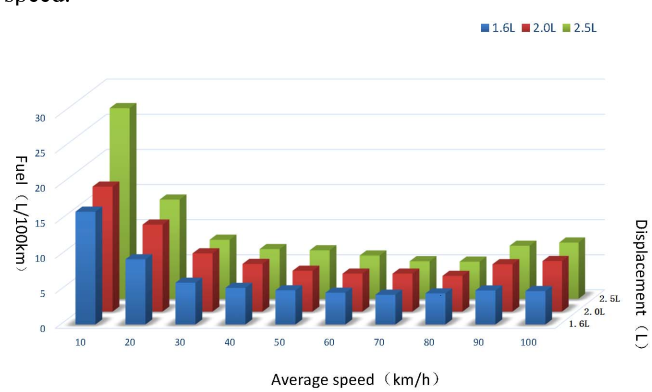

Figure 4. Relationship of displacement, speed and fuel

As demonstrated in Fig. 4, the engine displacement accelerates the fuel consumption. In order to avoid the effect of engine displacement, we choose the data with a vehicle displacement of 1.6L to analyze.

IV. SENSITIVITY OF FUEL CONSUMPTION TO ROAD GRADE

A. The relationship of speed and fuel consumption

Vehicle's instant fuel consumption is not only impacted by the current driving pattern (vehicle's driving state parameters, for example, instant speed, instant acceleration, etc.), but also the history one. In the case following, vehicle A runs at a constant speed of 50km/h, vehicle B speeds up to 50km/h from 20km/h, vehicle A and B are in the same type and run on the same links. The fuel consumption of A and B may be at the same level at a moment, but in a long term, the fuel consumed along the links for vehicle B is far higher than vehicle A. In order to estimate the sensitivity of fuel consumption to road grade accurately, we here consider the average fuel consumption instead of instant fuel consumption.

Because of the complex road physical structure of road network in Beijing, not only the road grade, but also the entrance, the traffic lights and the bus stops will affect the driving pattern, further, the fuel consumption. Here we chose the sections with only the attribute of road grade, for example, sections around the overpasses. The road grade can be changed between -4% and 4%.

Here we abstract about 50000 records driving data on 135 links, including instant speed, position data, distance in a second and the vehicle specification data. After a statistics, it seems that it differs obviously from each other of flat road and uneven road when it is divided by around 300 meters. The length of the 135 links here all satisfies this condition. After data cleaning, road matching, the average speed and the corresponding average energy driving on each link can be calculated, the relationship on both the uphill and the flat sections is shown below in Fig.5.

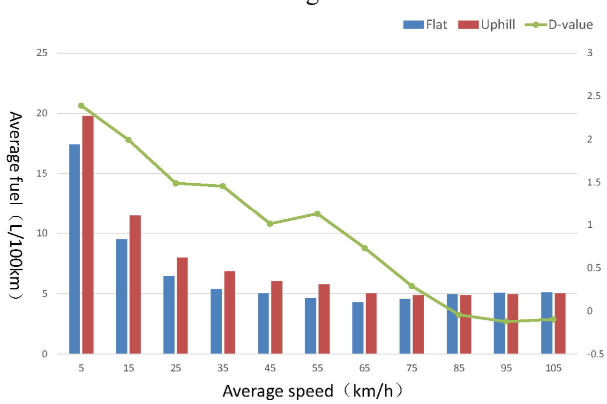

Figure 5. Comparion of flat road and uphill

As displayed in Figure 5, the impact of road grade on fuel consumption can't be underestimated. When the vehicle runs at a low speed [i.e, 0-25km/h], the traffic flow and the driving style always caused a high fuel consumption both on the flat road and the uneven road. The low speed always indicates a high congestion which will cause frequent starts and stops and so there are not enough time for oxygen in, the fuel can't fully burn and is wasted. Furthermore, a low speed will extend the travel time and the vehicle need to overcome the friction and the vehicle's own gravity for a longer time. When the traffic is better, vehicle speeds up and runs in a free state, there are less obvious acceleration and deceleration behaviors, which means the fuel can burn fully. The gap of the fuel on the two type of road can be 2.6L/100km and when the vehicle speeds up, the gap becomes smaller gradually.

B. The impact of road gradient on fuel consumption

It differs when the roads inclination are different of the work a vehicle need to do to overcome its own gravity and friction of road, the fuel consumption varies (see Fig. 6).

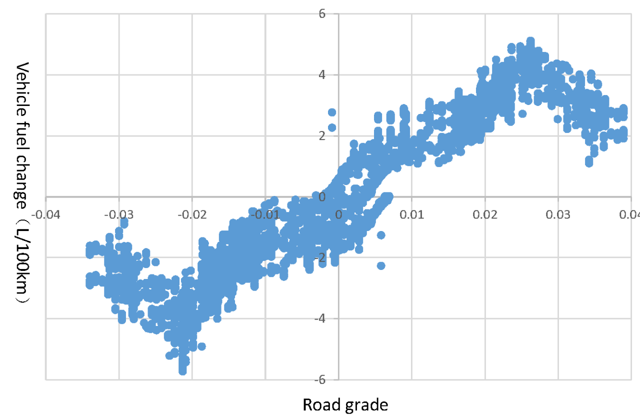

Figure 6. Fuel change due to the road gradient

As shown in Figure 6, compared with the flat road, the vehicle consume more fuel traveling uphill. When the road gradient increases, the fuel increases apparently. The fuel consumed is 4.3L/100km peak higher than flat road when the gradient is 2.6%. As the gradient continues to increase, the driver continues to gas in order to maintain a constant traveling speed, in this situation the fuel burn fully and the inertia of high speed pushes the vehicle, as a result, the fuel consumed decreases.

Due to the inertia of history running, the driver does not need to gas when traveling downhill, the engine is inoperative, and there is no need to burn fuel or just need little, the average fuel consumption drops 1.8L/100km when comparing with the data on flat road. The gap reaches the maximum when the gradient comes to -2.13%. If it is more inclined, the vehicle slipped obviously and speed up spontaneously. For the comfort and safety, the driver always take actions to brake. The speed fluctuation is obvious and there are many accelerations and decelerations. The shift of speed is far slower than the injector, the computer need to control the injector to inject more for the engine is blocked. It causes an increase to maintain a steady work of the engine and the fuel may not be burn exactly which leads to a waste.

As shown in Figure 6, the curve is not centrosymmetric, indicating that the effects of uphill and downhill are not the same. When the vehicle is climbing a slope, the drivers' driving style is a subjective factor. However, when traveling downhill, the drivers need less gas and brake. The Pearson correlation coefficient of gradient and the fuel is 0.818 when uphill while it is 0.73 when downhill. The gradient plays an important role when it comes to the “Eco traveling”.

C. The impact of driving style on fuel consumption

Comparing the driving data before the slope for 300m with the data on the slope with a gradient about 2%, less fuel is needed if the vehicle rushes uphill at a high speed than the case in which the vehicle accelerates all over the slope. In the former case, the driver does not gas obviously, the vehicle runs under the inertia and need only to overcome the friction and its own gravity, however, the travel time is prolonged. In the latter, the vehicle speeds up to climb the slope in a short time, the engine need to burn fuel to ensure a rapidly increasing speed, the more fuel lead to a higher fuel/air ratio, which means there is not enough oxygen for the fuel to burn fully and a lot of fuel is wasted. However, when comparing with the two cases, as shown in Fig.7 and Fig.8, uniform traveling do a compromise of traveling time and the engine’s work, the fuel is saved. The smaller of the variance of speed before and on the slope, the less fuel is consumed. In addition, if the vehicle speed up before the slope for about 300m and do a little acceleration on the slope just to maintain a constant speed, the fuel consumption will drop.

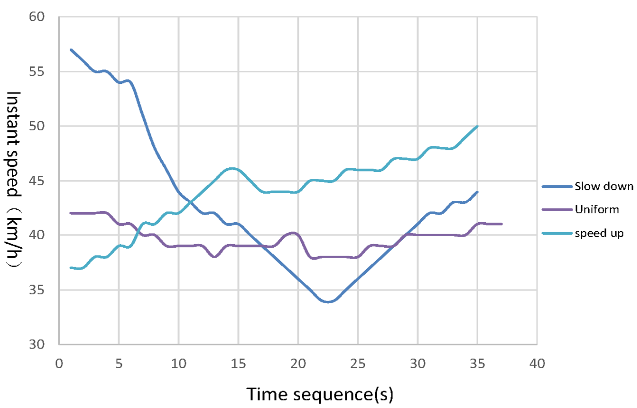

Figure 7. Vehicles’ traveling trajectories

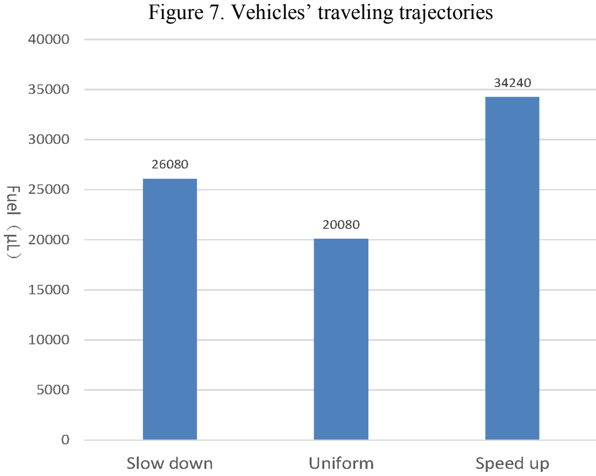

Figure 8. Fuel consumption under different driving style

CONCLUSION

Road grade is an important factor when building a transport vehicle fuel consumption model and choosing an ecological route. This work demonstrated the importance of accounting for road gradient and analyzed the impact of road grade to the fuel consumption based on the instantaneous driving data and the gradient calculated by the elevation data derived by the Google earth DEM.

Data of vehicles traveling on both the slope and the flat road shows that more fuel is consumed in the low-speed range (0,25km/h) and the gap between the two cases is large. As the vehicle speeds up, either the fuel consumed or the gap comes down.

Combined the driving data with the gradient of links in the road network, the relationship between the fuel and the gradient is get. The variance of fuel consumption get its peak when the gradient is 2.6%. In addition, different driving styles around the slope have an effect on the fuel consumption. While this research focused on the fuel consumption, it is expected that road gradient will be considered in the vehicle consumption model and the vehicle’s navigation system.

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