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Research on Optimization of Vehicle Driving from the Perspective of Saving Energy

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Abstract: Optimization of vehicle driving can reduce energy consumption and carbon emission. According to analyzing the differences of time constraints, two driving situations are proposed. In this study, vehicle energy-consumption models based on energy consumption minimization are built and the soft such as MATLAB is employed to solve the models. By calculating, minimal energy-consumption value and related variable values on different driving distances or time constraints are got which contribute to guiding drivers taking energy-consumption driving behaviors.

Key words: Energy-saving and low-carbon, driving behavior, vehicle energy-consumption model, energy-consumption optimization

INTRODUCTION

In recent years, road transportation industrial has achieved rapid development in promoting the development of society and economy and also brought a series of negative side effects. The first problem is energy consumption problems. Transportation industry is one of the fastest growing industries in energy consumption. In the United State, transportation system consumes 60% of total fuel, of which 73% are consumed by road transport (Khan, 1996); while in Canada transportation system accounts for 66% and almost all are consumed by road transport. In China, transportation fuel consumption generally takes 30% and transportation energy consumption takes about 7% in total energy consumption (Zhang *et al*., 2003). Considering the shortage of petroleum resources, transportation system's excessive dependence on petroleum resources would seriously affect the future economic growth. The second problem is ecological environment problems. The increase of number of vehicles inevitably causes higher emissions.

In all means of transportation, road transport emissions of greenhouse gas take 78% (Bektas and Laporte, 2011). China's statistics also shows that in urban atmospheric pollution, locomotive tail gas pollution takes 20-50% while in Shenzhen the rate reaches as high as 70% and the specific gravity are still in growing (Gui and Zhang, 2010). Pollutants accumulation produced by urban vehicles will surpass the self-purification ability of environment and destroy the balance of urban ecological environment.

It is necessary to adopt various means to alleviate negative effects such as consumption and carbon emissions brought by road transport. Optimization on vehicle driving, having important significance on energy-saving and low-carbon to the whole road transport system, is an effective means which deserves further study. At present, research on optimization of railway train automatic driving schemes are more and focus on ATO train algorithm (Wang, 2011; Ge, 2011; Xu, 2008). Car driving optimization mainly research on driving optimization decision based on driving behaviors like car-following driving, free travel driving and lane-changing driving (Reuschel, 1950; Pipes, 1953; Ahmed *et al.*, 1996; Ahmed, 1999; Wen *et al.*, 2006). Many scholars research on vehicle driving routing problems based on energy-saving and low-carbon (Kolb and Wacker, 1995; Xiao *et al.*, 2012; Bektas and Laporte, 2011). To achieve optimization objects of energy-saving and low-carbon, this study focuses on the decisions of variables like acceleration, speed and time under free travel diving model from different views. At first, two driving situations are proposed which one is with time constraints and the other is not, then optimization models are built and solved, finally optimization results are analyzed.

Problem analysis: The basis situation of vehicle driving is: Vehicle drive from standstill and operation process is divided into three stages. The first stage (acceleration phase) is: Speed up at the uniform acceleration of a and operation after t_a speed reaches $v_{t_a} = at_a$. The second stage (uniform phase) is: Keep constant speed till t_b. The third phase (decelerating phase) is: Keeping speed-down, vehicle is still when time is t_c and the total running distance is S. The question is: How does the vehicle drive

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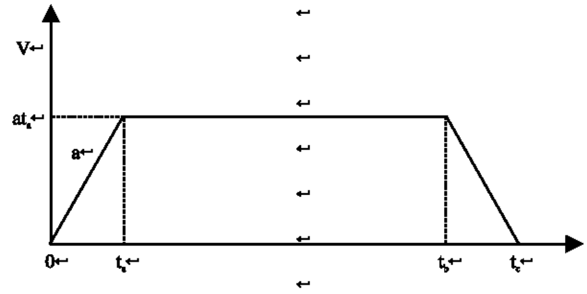

Fig. 1: Relationship between running speed and the time of vehicles

that can minimize fuel consumption or carbon emissions. The relationship between operation speed and time is shown in Fig. 1. Considering that vehicle fuel consumption and carbon emissions are positively linear correlation, for simplicity, the minimization of energy consumption is the optimization target in this study.

Fuel instantaneous consumption model, invented by Bowyer (1985), are used to present fuel consumption rate of vehicles:

$$f_t = \begin{cases} s + \beta_1 R_t v + (\beta_2 Ma^2 v) & \text{for} R_t > 0 \\ s & \text{for} R_t \leq 0 \end{cases}$$

In this model, f_t is fuel consumption per unit time (fuel consumption rate, the unit is mL sec^{-1}); R_t is traction (kN), the sum of air resistance and inertial force (without considering gradient force produced by slope) and $R_t = b_1+b_2v^2+Ma$. S is fixed fuel rate at the idle speed, S = 0.375~0.556 mL sec^{-1}. β_1 is fuel consumption per specific energy, β_1 = 0.08~0.09 mL kJ^{-1}. β_2 is accelerated fuel consumption per specific energy, β_2 = 0.02~0.03 kJ m sec^{-2}. b_1 is rolling resistance, b_1 = 0.1~0.7 kN. b_2 is rolling air resistance, b_2 = 0.00003~0.0015 KN/(m sec^{-2}). a is instantaneous acceleration (m sec^{-2}), M is weight (t), v is velocity (m sec^{-1}).

Vehicles in the operation of the third stage: Vehicle speed decreases from $v_{t_a} = at_a$ to 0 at the maximum deceleration of a_{max}, then driving distance is $(at_a)^2/2a_{max}$. a_{max} is the maximum deceleration and the general value under good road conditions is 4~8 m sec^{-2}. Braking time is $t_e = v/a_{max} = at_a/a_{max}$, then $t_c = t_b+t_e$.

Fuel consumption rate and fuel consumption of three phases are as follows:

$$f_1 = s+\beta_1R_tv+(\beta_2Ma^2v) = s+\beta_1(b_1+b_2v^2+Ma)v+\beta_2Ma^2v$$

$$f_2 = s+\beta_1R_tv = s+\beta_1(b_1+b_2v^2+Ma)v$$

$$f_3 = s$$

According to differences of the time constraints, two situations are divided:

- **Situation 1:** Finishing the whole driving process without time constraints
- **Situation 2:** Finishing the whole driving process with time constraints

For the two situations, optimization models are built separately and the results are analyzed and compared.

OPTIMIZATION UNDER SITUATION 1

Build model: Build the objective function on minimization of energy-consumption:

$$\text{MinF} = \int_0^{t_a} f_1 dt + \int_{t_a}^{t_b} f_2 dt + \int_{t_b}^{t_c} f_3 dt = st_c + \frac{\beta_1 b_2 a^3}{4} t_a^4 + \frac{(\beta_1 b_1 a + \beta_1 Ma^2 + \beta_2 Ma^3)}{2} t_a^2 + (\beta_1 b_1 at_a + \beta_1 b_2 a^3 t_a^3)(t_b - t_a)$$

Constraint conditions s.t.:

$$\begin{cases} S = \frac{1}{2}at_a^2 + at_a(t_b - t_a) + (at_a)^2 / 2a_{max} \\ t_c = t_b + at_a / a_{max} \\ a > 0 \\ 0 < t_a \leq t_b \end{cases}$$

Model solving: The above model is nonlinear programming with constraint conditions for minimum, with the application of MATLAB toolbox to solve. Fmincon function is used to solve based on characteristics of model. a, t_a, t_b, t_c are model variables. Parameters are set as follows:

$$s = 0.45,\ \beta_1 = 0.085,\ \beta_2 = 0.025,\ M = 2.5,\ b_1 = 0.4,\ b_2 = 0.001,\ a_{max} = 6$$

Table 1 is optimization results and Fig. 2 is relationship between acceleration, running time, top speed, fuel consumption value and velocity.

By analyzing, conclusions are as follows:

- Fuel consumption value F, time t_a, t_b, t_c and top speed v_{max} increase gradually with the increasing of driving distance S, however acceleration a in acceleration phrase is on the contrary
- The equation $t_b \neq t_a$ means uniform phrase is existed and constant speed running increases with the increasing of driving distance S. The operation schematic diagram is shown in Fig. 3

Table 1: Calculation results of situation I

Distance S (m)	Acceleration a (m sec^{-2})	Time t_a (sec)	Time t_b (sec)	Time t_c (sec)	Top speed v_{max} (m sec^{-1})	Minimum value of fuel consumption F (mL)
100	1.1763	4.3673	21.2216	22.07781	5.137255	17.0484
200	1.0428	6.1887	33.5479	34.62350	6.453576	28.4630
300	0.9731	7.5231	44.1289	45.34902	7.320729	38.7892
400	0.9275	8.5924	53.8238	55.15204	7.969451	48.5670
500	0.8943	9.4864	62.9735	64.38745	8.483688	58.0096
600	0.8686	10.2534	71.7533	73.23765	8.906103	67.2260
700	0.8480	10.9228	80.2667	81.81046	9.262534	76.2799
800	0.8309	11.5146	88.5798	90.17438	9.567481	85.2123
900	0.8164	12.0431	96.7377	98.37636	9.831987	94.0508
1000	0.8027	12.5403	104.7780	106.45570	10.066100	102.8148
1100	0.7932	12.9496	112.7075	114.41940	10.271620	111.5188
1200	0.7837	13.3422	120.5607	122.30340	10.456280	120.1734
1300	0.7753	13.7017	128.3454	130.11590	10.622930	128.7870
1400	0.7677	14.0322	136.0728	137.86820	10.772520	137.3661
1500	0.7609	14.3373	143.7512	145.56940	10.909250	145.9158
1600	0.7548	14.6198	151.3875	153.22670	11.035030	154.4402
1700	0.7492	14.8824	158.9874	160.84570	11.149890	162.9429
1800	0.7440	15.1269	166.5557	168.43140	11.254410	171.4265
1900	0.7393	15.3554	174.0961	175.98810	11.352250	179.8935
2000	0.7350	15.5693	181.6121	183.51930	11.443440	188.3459

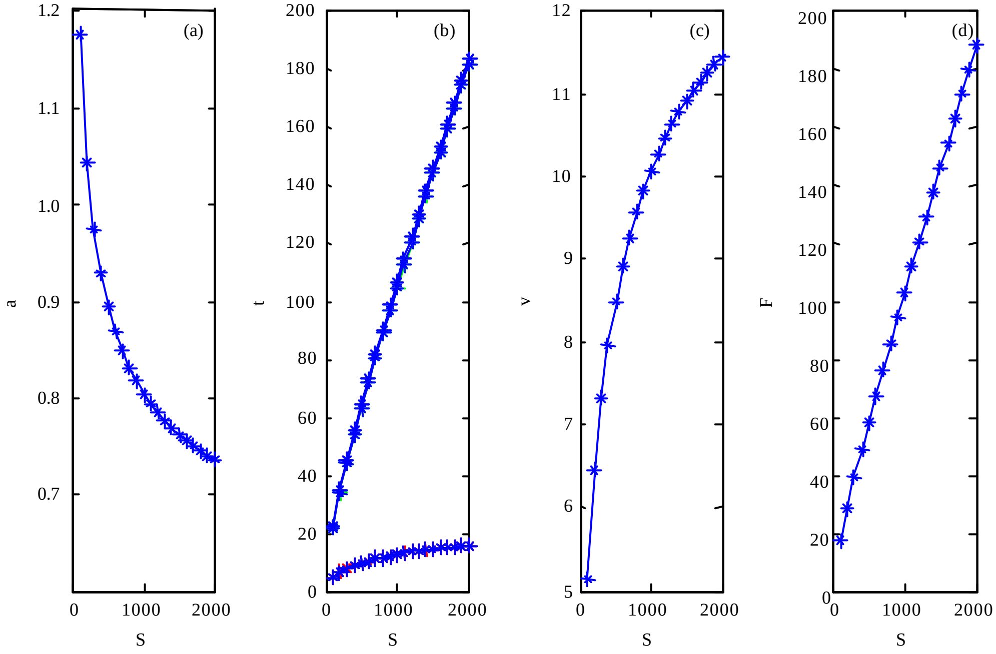

Fig. 2(a-d): Relationship between variables and distance

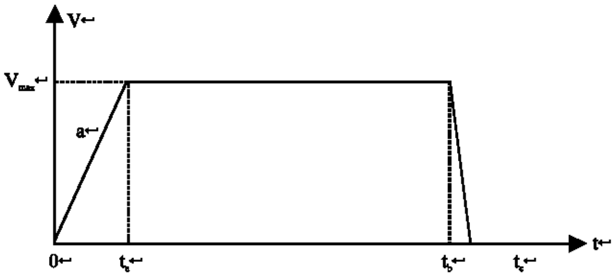

Fig. 3: Operation schematic diagram of situation 1

Table 2: Calculation results of situation 2

Time t_0 (sec)	Acceleration a (m sec^{-2})	Time t_a (sec)	Time t_b (sec)	Time t_c (sec)	Top speed v_{max} (m sec^{-1})	Minimum value of fuel consumption F (mL)
20	33.8499	2.5967	5.3503	20.0000	87.8982	9207.9.00
30	5.5254	8.1693	22.4768	30.0000	45.1391	736.1616
40	3.0935	9.9613	34.8641	40.0000	30.8153	308.9786
50	2.1603	10.8627	46.0888	50.0000	23.4670	191.4274
60	1.6623	11.4125	56.8382	60.0000	18.9707	144.2190
70	1.3515	11.7859	67.3452	70.0000	15.9287	121.9563
80	1.1388	12.0576	77.7115	80.0000	13.7312	110.8049
90	0.9840	12.2651	87.9886	90.0000	12.0683	105.3591
100	0.8661	12.4294	98.2057	100.0000	10.7656	103.1459
110	0.8040	12.5187	104.7724	106.4500	10.0652	102.8148
120	0.8040	12.5187	104.7724	106.4500	10.0652	102.8148

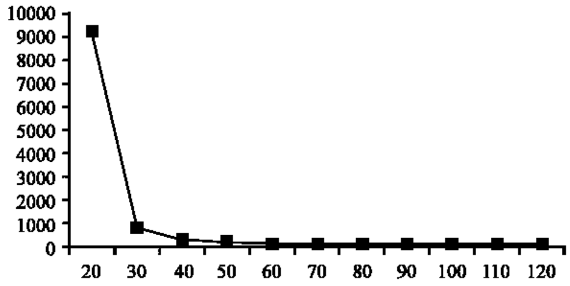

Fig. 4: Relationship between energy consumption and time

OPTIMIZATION UNDER SITUATION 2

Build model: The second situation has total time constraint which requires $t_c \leq t_0$. The optimization model is built as follows:

$$\mathrm{MinF} = \int_0^{t_a} f_1 dt + \int_{t_a}^{t_b} f_2 dt + \int_{t_b}^{t_c} f_3 dt = st_c + \frac{\beta_1 b_2 a^3}{4} t_a^4 + \frac{\left(\beta_1 b_1 a + \beta_1 Ma^2 + \beta_2 Ma^3\right)}{2} t_a^2 + \left(\beta_1 b_1 at_a + \beta_1 b_2 a^3 t_a^3\right)\left(t_b - t_a\right)$$

Constraint conditions: s.t.:

$$\begin{cases} S = \frac{1}{2} at_a^2 + at_a\left(t_b - t_a\right) + \left(at_a\right)^2 / 2a_{max} \\ t_c = t_b + at_a / a_{max} \\ a > 0 \\ 0 < t_a \leq t_b \\ t_c \leq t_0 \end{cases}$$

Model solving: The main parameters of the model are the same with the first situation, when S = 1000 m, using Matlab to operate, get the optimization results while t_0 is different, the results are shown in Table 2.

The relationship between energy consumption and time is shown in Fig. 4.

By analyzing, conclusions are as follows:

- When $t_0 \geq 106.45$ sec, the minimum fuel consumption is 102.8 mL
- When $t_0 < 106.45$ sec, the smaller the t_0 is, the larger the fuel consumption is
- The smaller the t_0 is, the more sensitive the fuel consumption is. When $t_0 \to 0$, the ful$\to\infty$

CONCLUSION

The study puts forward two driving situations, optimizes each situation and calculates minimum value of fuel consumption and related variable values in different distances. Conclusions, having impact on low-carbon and energy-saving of vehicles driving, are drawn by comparing and analyzing results of optimization under two situations. Means of transport like locomotive and plane are easier to ensure automated control than vehicles. Therefore, low-carbon and energy-saving driving of those transports needs further study.

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