

A Statistical Evaluation Model for Driver-Bus-Route Combinatorial Optimization

Denggao Huang^{1†}, Hui Xie¹, Qiang Sun¹, Hongjie Ma¹, Tielong Shen²

1.State key laboratory of engines, Tianjin University, Tianjin, China
(Tel: +86-022-2740-7723; E-mail: xiehui@tju.edu.cn)

2. Department of Engineering and Applied Sciences, Sophia University, Tokyo 102-8554, Japan
(E-mail: tetu-sin@sophia.ac.jp)

Abstract: Bus fuel economy is closely related to driver's habits and driving conditions. How to efficiently arrange drivers, buses and routes with better fuel economy is a difficult problem for bus companies. This paper aims to propose a statistical evaluation model for this problem. The features of bus configurations, driver operations and driving routes were analyzed, and 6 key factors were defined to represent their effects on fuel economy, which are bus design optimal velocity, bus design optimal acceleration, driver desiring velocity, driver desiring acceleration, mean velocity of bus route and mean acceleration of bus route. Based on the power balance of driver-bus-route, the problem of driver-bus-route optimization can be depicted by driver, bus and route statistical points. The sum of weighted distance of three points can be set as the evaluation index of driver-bus-route arrangement. This statistical valuation model was finally applied with the monitor data from 11 drivers, 2 bus lines and 2 typical buses for more than one year. The data analysis results show that the sorting result of evaluation index is consistent with fuel economy and the proposed evaluation index can effectively predict the fuel economy level of driver-bus-route arrangement. By comparing the evaluation index of the statistical evaluation model, a relatively optimal arrangement of bus-driver-routes for fuel saving can be achieved.

Keywords: Driver-bus-route, city bus, arrangement, optimization

1. INTRODUCTION

Energy consumption of a city bus depends on various physical factors, such as characteristics of its engine, the powertrain system, the structure of bus against aerodynamic drag, road surface conditions, and the weather. Besides these factors, driving behaviors and driving conditions also have a great influence on fuel consumption. Driving behavior differences can contribute, in total, to about 45% reduction of the on-road fuel economy [1]. The vehicle fuel economy and emission are also deeply affected by driving condition. Therefore, how to efficiently arrange vehicle fleet and drivers with better fuel economy is a difficult issue. The issue is very important for bus companies and often solved by the manager's experience. A statistical valuation model is proposed to solve this issue, based on the relations of driver-bus-route.

The issues of optimal arrangement of buses, drivers and routes can be summarized as two points: 1) Abstracting main factors of driver-bus-route relative to bus fuel economy; 2) Developing an evaluation model to assess their influence and giving advices for better arrangement of buses, drivers and routes. The driver-bus-road factors affecting on fuel economy are mostly illustrated by Ericson [2-4]. Ericson abstracted 16 characters to describe fuel sensitive factors from drivers, driver operations, road types and vehicle types, and intended to give an influence scope of street characteristics, driver categories and car performance. In the field of driver-bus-route matching evaluation model (DBRME), Zhu W. developed a model framework for the independent measurement of bus operating efficiency and quality of bus service to analyze the effects of external operating environment on the performance of bus routes [5]. Barnum, D. used Data

Envelopment Analysis scores to account for the environmental influences [6]. Furthermore, Site P. D. proposed a formulations model of optimal bus service in urban areas, considering service level, price and bus size, with fuel saving objective and various financial constraints [7]. Yu, Bina set up a model for optimizing bus route headway by parallel genetic algorithm, aiming to find an acceptable balance between passenger costs and operator costs, namely the maximization of service quality and the minimization of operational costs [8].

This paper aims to abstract a series of statistical parameters to represent features of drivers, buses and routes. An evaluation index of driver-bus-route is proposed for efficient arrangements, based on Matching Rule of Driver-Bus-Route (MRDBR). With the Matching Rule of Driver-Bus-Route, the driver can steer bus at its optimal efficient working surfaces, and be subjected to driving cycle of bus route.

This paper is organized as follows. In section 2, the features of driver, bus and route are defined based on bus kinematical formulation and driver-bus-route evaluation index for efficient arrangement is proposed. This method is applied to driver-bus-route arrangement evaluation of two bus line in section 3. The advantages and drawbacks of this method are discussed in section 4. Conclusions are made in section 5.

2. METHODOLOGY

2.1 Factors affecting bus fuel economy

The bus running resistance consists of 4 forces: rolling resistance, aerodynamic resistance, grade resistance, and inertia resistance. The bus dynamical resistance force is as following Eq. (1).

$$F_f = mgf\cos\theta + \frac{C_d A v^2}{21.15} + mg\sin\theta + ma \quad (1)$$

[†] Denggao Huang is the presenter of this paper. This work was supported by the International Science and Technology Cooperation Program of China (2013DFG62890) and the National Nature Science Foundation of China (51307119).

Where C_d , A , f , m , g and θ are air drag coefficient, frontal area of bus, rolling resistance coefficient, mass, gravity and the road grade, respectively. a , v are bus acceleration (m/s^2) and velocity (km/h) respectively.

The traction force is related by transmission ratio and engine brake torque, as Eq. (2).

$$F_d = T_e i_0 i_g D_c / R \quad (2)$$

Where F_d , T_e , R , i_0 , i_g are tire driving force(N), engine brake torque(Nm), wheel radius(m), main ratio and gearbox ratio, respectively. D_c is the state of clutch, when the clutch is engaged, $D_c = 1$, and when the bus is in neutral and declutched, $D_c = 0$. Based on bus kinematic dynamic, the relation between bus velocity and engine speed is shown in Eq. (3).

$$N_e = \frac{v}{2\pi R} i_0 i_g D_c \quad (3)$$

Based on the control map of fuel injection in engine control unit, the mass flow of diesel engine is determined by brake torque and the engine speed (rpm). Engine fuel consumption model can be depicted as Eq. (4) and Eq. (5). Where T_e , N_e , P_e , \dot{P}_e are engine brake torque(Nm), engine speed(rpm), output power of engine(Kw) and change rate of output power. C_i , k_2 and k_1 are coefficients. Q_{FE} (kg/h) is the fuel consumption under transient operating conditions of engine.

$$Q_{FE} = \sum_{i=0}^3 C_i (1 + k_1 \dot{P}_e^2) P_e^i \quad (4)$$

$$P_e = k_2 N_e T_e \quad (5)$$

Based on the control strategy of driving operations in an electronic control unit (ECU), the output torque of engine is determined by the engine speed N_e and the depth of accelerator pedal A (%).

$$T_e = \sum_{i+j=0}^3 k_{(i,j)} N_e^i A^j \quad (6)$$

Based on Eq. (3) to (6), the bus transient fuel economy model can be summarized as Eq. (7).

$$Q_{FE} = f\left(A, v, \frac{dA}{dt}, \frac{dv}{dt}, i_g\right) \quad (7)$$

In Eq. (7), accelerator pedal percentage (A), acceleration pedal changing rate (dA/dt), gear selection (i_g), driving speed (v) and driving acceleration (dv/dt) are the key factors for bus fuel economy. They can be used as reference features of bus configuration, driver operation and driving route.

2.2 Features abstraction of driver-bus-route system

2.2.1 Description of driver features

Based on Eq. (7), Accelerator pedal percentage, accelerator pedal changing rate and gear selection are the driver decision outputs. Gear selection and shift time are usually determined by powertrain configuration. With the development of auto manual transmission technology, gear selection is less influenced by driver habits. Accelerator pedal percentage and accelerator pedal changing rate are the representations of driver's demand of driving speed and acceleration [9]. They are

closely related to the driver habits and fuel consumption. The probability density functions of accelerator pedal percentage and changing rate are calculated to represent driver demand habits. The process methods are shown in Eq. (8) and Eq. (9).

$$y_{d_accpedal} = f(A), v \in [0, 100] \quad (8)$$

$$y_{d_accrate} = f\left(\frac{dA}{dt}\right), A \in [0, 100] \quad (9)$$

Where, $y_{d_accpedal}$, $y_{d_accrate}$ are the probability density of accelerator pedal percentage and changing rate.

The drivers often adjust pedal depth and changing rate to follow front vehicles[10]. A linear model is proposed to describe the relation between (Accelerator pedal percentages, accelerator pedal changing rate) and (desiring speed, desiring acceleration). The relations are following Eq. (10) and Eq. (12).

$$V_{driver} = K1 \times A \quad (10)$$

$$Acc_{driver} = K2 \times \frac{dA}{dt} \quad (11)$$

Where, V_{driver} represents driver desired speed (km/h), Acc_{driver} represents bus acceleration expected by driver accelerator pedal changing rate (m/s^2). $K1$ and $K2$ are defined as transform coefficient here (km/%), and calculated by empirical dataset.

Based on the Eq. (8) to Eq. (11), the probability density functions of desired speed and acceleration are calculated as Eq. (12) and Eq. (13).

$$y_{v_driver} = K1 \times f(A), v \in [0, 100] \quad (12)$$

$$y_{v_acc} = K2 \times f\left(\frac{dA}{dt}\right), A \in [0, 100] \quad (13)$$

Where, y_{v_driver} and y_{v_acc} are the probability density of driver desired speed and acceleration.

2.2.2 Description of bus optimal features

For bus powertrain system, there are optimal design running speed and acceleration curves. The solving equations are shown as Eq. (14) below.

$$(V_{veh_Opti}, a_{veh_Opti}) = \min_{fuel\ economy} \{F(BSFC, f_r, R, i_g)\} \quad (14)$$

Where, V_{veh_Opti} , Acc_{veh_Opti} are bus optimal design speed (km/h) and optimal design acceleration (m/s^2), BSFC is engine universal characteristic ($g/(kw \cdot h)$), f_r , R , i_g denote the rolling resistance of bus rolling resistance coefficient, tire radius and gears. The bus economy working point of (V_{veh_Opti} , Acc_{veh_Opti}) is attributed to bus feature.

2.2.3 Description of route driving cycle feature

Bus speed and acceleration is the power demand of driving cycle, so the main features of bus route are the distributions of speed and acceleration [11]. Statistical distribution density of speed and acceleration for bus lines can be calculated as Eq. (15) to (16).

$$y_{v_route} = f(v), v \in [0, 70] \quad (15)$$

$$y_{a_route} = f\left(\frac{dv}{dt}\right), v \in [0, 70] \quad (16)$$

Where, y_{v_route} is the probability density of route speed v (km/h), y_{a_route} is probability density of acceleration a (m/s²).

2.3 Method of constructing statistical model

The distributions of accelerator pedal percentage and changing rate represent driver power. Bus design optimal speed-acceleration is the efficient output power of bus working point. The product of speed and acceleration is the basic driving power demand management for route driving cycle. The power character relations between driver-bus-route are shown in the Fig.(1). The black filled areas of Fig.(1) is the efficient arrangements, in which drivers can steer bus at its optimal efficient working points, and be subjected to driving cycle of bus route.

Based on driver-bus-route distribution characters, the efficient match arrangement of drivers, buses and routes, is a multi-distribution matching problem of drivers, buses and routes.

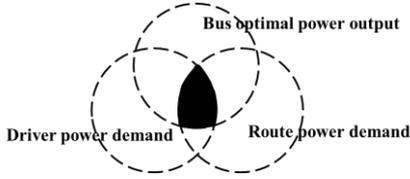


Fig. 1 Power relations of driver-bus-route system

The basic principles of statistics illustrate that statistical mean value is consistent with the characteristics of statistical distribution. Therefore, the multi-distribution features matching problem can be simplified to statistical mean values matching problem. Schematic of efficient match arrangements is shown in figure 2.

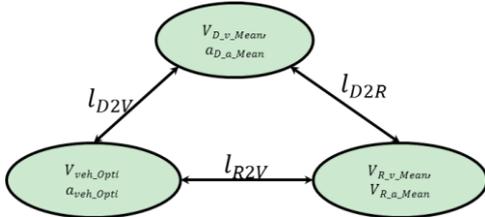


Fig.2 Matching triangle of driver-bus-route

Based on the Eq.(12), Eq.(13), Eq.(15) and Eq.(16), the calculations of statistical mean values are as following Eq. (17) to Eq. (20).

$$V_{D,v,Mean} = \int_0^{100} K1^2 \times A \times f(A) dA \quad (17)$$

$$a_{D,a,Mean} = \int_0^{100} K2^2 \times \frac{dA}{dt} \times f\left(\frac{dA}{dt}\right) d\left(\frac{dA}{dt}\right) \quad (18)$$

$$V_{R,v,Mean} = \int_0^{70} v f(v) dv, v \in (0, 70] \quad (19)$$

$$a_{R,a,Mean} = \int_0^{70} \left(\frac{dv}{dt}\right) f\left(\frac{dv}{dt}\right) d\left(\frac{dv}{dt}\right), v \in (0, 70] \quad (20)$$

Where, $V_{D,v,Mean}$, $a_{D,a,Mean}$ are feature parameters of driver (desired speed(km/h), desired acceleration(m/

s²)), $V_{R,v,Mean}$, $V_{R,a,Mean}$ are feature parameters of route driving cycle (average speed(km/h), average acceleration(m/s²)). Particularly, city bus idling stop condition is not included, in which bus fuel consumption is often constant. Impact of transit vehicle brake pedal kinetic energy loss is not considered, because the proportion of fuel consumption is relatively small and above 50% energy is consumed during the acceleration of a city bus [12].

In which, l_{D2V} , l_{R2V} , l_{D2R} are defined as evaluation index of Driver-Bus, Route-Driver, Driver-Route. The calculation equation of l_{D2V} , l_{R2V} , l_{D2R} are shown in Eq.(21), Eq(22), Eq(23). If the value of evaluation index is small, the components of driver-bus-route are better matched.

$$l_{D2V} = \frac{1}{\sqrt{(V_{D,v,Mean} - V_{veh,Opti})^2 + (a_{D,a,Mean} - a_{veh,Opti})^2}} \quad (21)$$

$$l_{R2V} = \frac{1}{\sqrt{(V_{R,v,Mean} - V_{veh,Opti})^2 + (a_{R,a,Mean} - a_{veh,Opti})^2}} \quad (22)$$

$$l_{D2R} = \frac{1}{\sqrt{(V_{D,v,Mean} - V_{R,v,Mean})^2 + (a_{D,a,Mean} - a_{R,a,Mean})^2}} \quad (23)$$

Based on the matching rule (MRDBR), the sum of weighted distance between driver, bus and route can be calculated as Eq. (24).

$$l_{D,V,R} = \alpha l_{D2V} + \beta l_{R2V} + \gamma l_{D2R} \quad (\alpha, \beta, \gamma > 0) \quad (24)$$

Where, α, β, γ are the weighting coefficients for driver-bus-route matching, and can be calibrated by experimental data. $l_{D,V,R}$ represents evaluation index of driver-bus-route arrangement. When $l_{D,V,R}$ is small, the better arrangements of driver-bus-route.

The coefficients can be calculated by the rank of driver-bus-route matching and fuel economy, as shown in Eq. (25). The coefficients are given by maximum R returned.

$$\{K1, K2, \alpha, \beta, \gamma\} = \max_R \{R | R = 1 - 6 \frac{\sum (l_{D,V,R}(i) - F(i))^2}{N(N-1)}\} \quad i=1,2,3,\dots,N \quad (25)$$

Where, R is the spearman coefficient between the estimated evaluation index and fuel economy of special driver-bus-route. $l_{D,V,R}(i)$ is the estimated evaluation index of the i_{th} driver-bus-route system. $F(i)$ is experimental fuel economy of the i_{th} driver-bus-route system. N is the simple number of driver-bus-route system.

3 APPLICATION AND RESULTS

To validate the proposed evaluation index ($l_{D,V,R}$), the actual operating data of Tianjin bus line 503, 516 were been acquired by public transportation vehicles OBD port. The acquisition data is more than 14600 cycles, covering four season of whole year.

The database includes six buses, 11 drivers with fuel

consumption, speed, pedal operation, gear, GPS and other information, which are recorded at a frequency of 10 Hz in SD card, meeting the accuracy requirements. The bus configurations are as follow table.

Table 1 Configuration of monitoring bus

	503 line	516 line
Bus type	YUT ZK6902HGA	SLK6905UF5
Engine	YC6J200-30	YC6J200-30
Gearbox Ratio	1/2/3/4/5 6.9/4.13/2.45/1.49/1	1/2/3/4/5 8.3/4.8/2.9/1.76/1]
Main ratio	5.571	3.75
Tire radius	0.53975m	0.469m
Roll coef.	0.0062551	0.0062551
Air coef.	0.67349	0.67349
Front area	7.7924m ²	7.84m ²
Drivers	6 drivers	5 drivers

503 line dataset was used to calibrate driver-bus-route statistical coefficients. 516 line dataset was used to validate the model prediction results. The results include feature analysis of bus, route driving cycle and driver pedal operations, and relations between distributions and statistical mean points of driver-bus-route system. Finally, the sorting result of evaluation index was evaluated.

3.1 Driver-bus-route features of 503&516line

3.1.1 Design optimal characteristics of city bus

Based on the bus mechanical design, the fuel economy features are showed in Fig.3 and Fig.4.

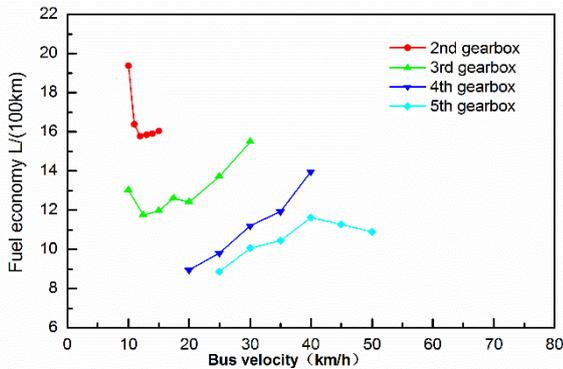


Fig.3 line 503 bus fuel economy feature

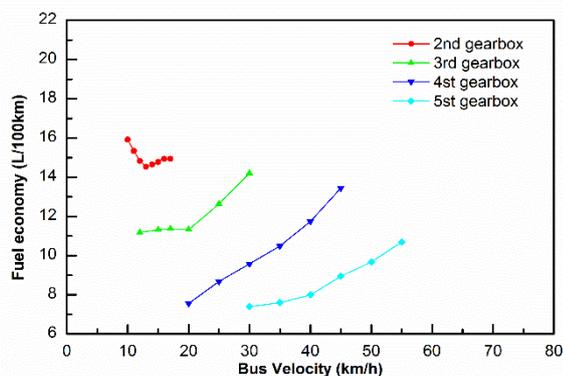


Fig. 4 line 516 bus fuel economy feature

The fuel consumption increased as the bus cruising speed increased. It can be inferred from[13] that, the increased vehicle acceleration led to increased fuel consumption. Therefore, the efficient state of city buses is cruising at its' optimal design velocity, and acceleration is zero. For the 503 line buses, the best economy working point is velocity at 20km/h and 4th gearbox. For the 516 bus, the best economy working point is velocity at 21 km/h and 4th gearbox.

3.1.2 Bus routes driving cycle features

For city bus line, the driving cycle reflects profile of route traffic conditions. The distributions of velocity and acceleration for 503 & 516 bus route are shown in Fig. 5 and Fig. 6.

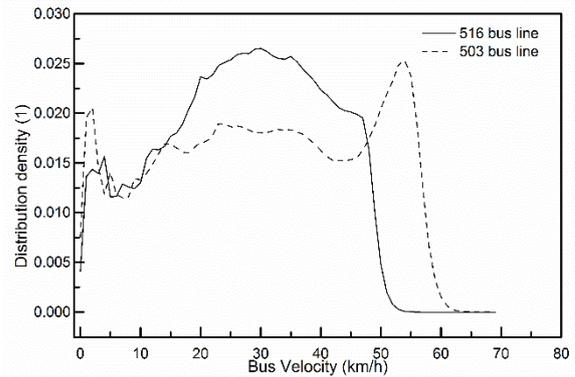


Fig. 5 Velocity density of 503&516 bus line

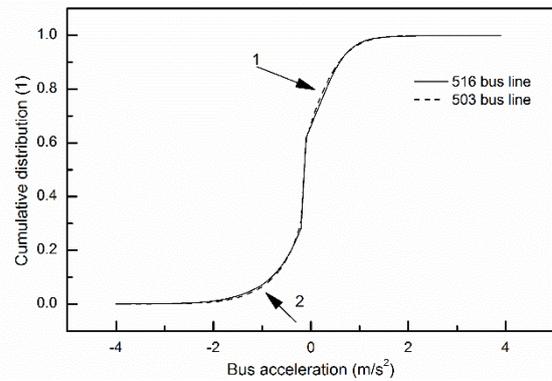


Fig. 6 Cumulative density of acceleration for 503&516

For bus line 503, it includes three territories, which are urban route, rapidway route and suburban route. The velocity density and cumulative density show three peaks. The first peak is bus velocity below 10km/h, which represents urban driving cycle. The second peak is bus velocity between 10km/h and 45km/h, which represents suburban driving cycle. The third peak is bus velocity between 45km/h and 70km/h, which represents rapidway driving cycle. Compared to velocity frequency of 503 line, 516 line is a typical suburban route. 67% of cumulative density of acceleration of 503 line and 516 line is below zero, which means that buses spend more time in deceleration.

Statistical average route speed and acceleration of

503 line are 31km/h and 0.41m/s². Statistical average route speed and acceleration of 516 line are 27km/h and 0.4m/s². As the arrow symbols 1 and 2 shown in figure 6, the driving cycle of 503 line is more aggressive than 516 line.

3.1.3 Driver pedal operation features

As statistics and analysis of data sets, frequency statistical data of drivers' Acceleration pedal are shown in Fig. 7 and Fig. 8 for line 503 &516. With the same route and type of bus, the distribution of accelerator position is totally different. With low acceleration pedal and smoothly acceleration operation, drivers tend to be lower fuel consumption[14]. 503Driver3 and 516Driver3 respectively have the most steep cumulative distribution line, which indicate that they will get much better fuel economy than other drivers . However, the accelerator pedal changing rate presents less difference for different drivers.

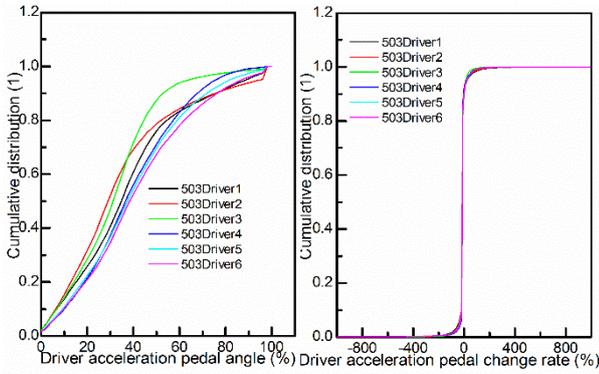


Fig. 7 Cumulative distribution of accelerator position and accelerator pedal changing rate for line 503

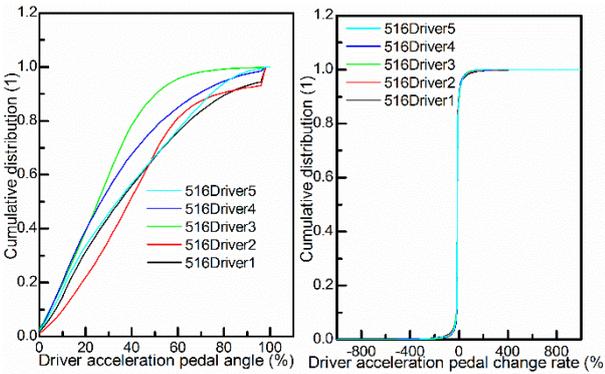


Fig. 8 Cumulative distribution of accelerator position and accelerator pedal changing rate for line 516

3.2 Driver-bus-route evaluation index of 503&516

3.2.1 Parameters calibration of Driver-bus-route evaluation model from data of line 503

From the theories of section 2 and Eq.(25), there are 5 parameters required to calibration by experimental data, which are K1, K2, α , β , γ . More than 20 bus routing rounds data are processed by each driver to reduce random errors. When Spearman correlation(R) is equal to the maximum 1 from fuel economy rank of 6 drivers of 503 line, the returned values of [K1, K2, α , β , γ] are [1,1/35,1,1,1], calculated by the Eq.(25).The calculation

results are shown in table 3. The driver-bus matching index (I_{D2V}), driver-route evaluation index (I_{D2R}) and bus-route evaluation index (I_{V2R}) are also spearman correlated with fuel economy.

Meanwhile, the driver desiring speed and acceleration are listed in table 2 for line 503. The rank of driver desiring speed (V_{D,v_Mean}) and acceleration (a_{D,a_Mean}) are consistent with the ramps in Fig.7 and Fig. 8.

Table 2 Desiring speed and acceleration of line 503

Driver No.	Size	V_{D,v_Mean} Km/h	a_{D,a_Mean} m/s ²
503Driver 1	73	38.31	0.55
503Driver 2	110	35.42	0.49
503Driver 3	146	32.32	0.41
503Driver 4	21	39.22	0.46
503Driver 5	27	40.32	0.48
503Driver 6	40	42.10	0.48

Table 3 Driver-bus-route evaluation index for line 503

Driver No.	Size	Fuel L/100k m	$I_{D,V,R}$	I_{D2R}	I_{D2V}	I_{V2R}
503Driver3	146	21.04	16.7	1.7	8.3	6.6
503Driver2	110	21.12	22.9	4.8	11.4	6.6
503Driver1	73	21.85	28.7	7.7	14.3	6.6
503Driver4	21	23.57	30.5	8.6	15.2	6.6
503Driver5	27	23.71	32.7	9.7	16.3	6.6
503Driver6	40	24.62	36.2	11	18.1	6.6
Spearman correlation			1	1	1	-

3.2.2 Prediction of driver-bus-route evaluation index for 516line

Based on the calibrated parameters [K1, K2, α , β , γ], the driver desiring speed and acceleration of line 516 are shown in table 4. The Driver-bus-route evaluation index of 516 line for all drivers are listed in table 5.

From the results of table 4 and table 5, the Spearman correlation between the estimated evaluation index ($I_{D,V,R}$) and fuel economy (Fuel, L/100km) of special driver-bus-route is 1. It reveals that this driver-bus-route evaluation index can be used as arrangement evaluation of drivers, buses and routes. The larger evaluation index $I_{D,V,R}$ yields higher fuel consumption, and vice versa. For evaluation index of driver-bus and driver-route, the rank of I_{D2R} and I_{D2V} is also useful.

Besides, the fuel economy of line 503 and line 516 is respectively 28km/h and 32L/100km in experimental database. The I_{V2R} of 503 line is smaller than 516 line. It means that the bus and route is relatively better arranged in line 503 than line 516.

Table 4 Desiring speed and acceleration of line 516

Driver No.	Size	V_{D,v_Mean} Km/h	a_{D,a_Mean} m/s ²
516Driver1	128	40.40	0.53
516Driver2	120	42.22	0.49
516Driver3	108	27.87	0.45
516Driver4	128	33.06	0.45
516Driver5	196	38.26	0.46

Table 5 Estimated Driver-bus-route evaluation index and monitoring fuel economy of line 516

Driver No.	Size	Fuel L/100km	$l_{D_V_R}$	l_{D2R}	l_{D2V}	l_{V2R}
516Driver 3	108	23.86	18.0	1.0	3.9	6.9
516Driver 4	128	24.86	28.4	6.2	9.1	6.9
516Driver 5	196	26.54	38.8	11.4	14.3	6.9
516Driver 1	128	27.71	43.1	13.5	16.4	6.9
516Driver 2	120	29.23	46.7	15.3	18.2	6.9
Spearman correlation			1	1	1	-

4 DISCUSSION

Reducing fuel consumption is very important for bus companies. Appropriate arrangement of drivers, buses and routes is effective and convenient for bus companies. However, it is challenging to quantify driver-bus-route evaluation index.

Based on the Matching Rule of Driver-Bus-Route and bus transient fuel economy model, 5 key factors are abstracted to demonstrate driver-bus-route features. 6 statistical parameters are defined to describe features of drivers, buses and routes. The evaluation index of l_{D2V} , l_{R2V} , l_{D2R} are defined to represent the evaluation rank of Driver-Bus, Route-Driver, Driver-Route.

Furthermore, the driver-bus-route evaluation index ($l_{D_V_R}$) is proposed to estimate evaluation level of buses, drivers and routes. The results show that $l_{D_V_R}$ is Spearman correlated with fuel economy. The driver-bus-route arrangement evaluation index can be sorted by $l_{D_V_R}$. When the $l_{D_V_R}$ is small, the match of driver-bus-route tends to relatively better.

Compared with previous work by other researchers, this method is primarily based on driver habits, bus kinematical configurations, and route driving cycle features, and closely related to bus fuel consumption mechanism. It's an easy way for bus companies to sort better driver-bus-route arrangements to improve fuel economy and minimize cost for all bus lines.

5 CONCLUSION

Based on the bus fuel economy model and analysis of driver-bus-route features, some conclusions are as follow.

- 1) By the analysis of bus transient fuel consumption model, accelerator pedal percentage, acceleration pedal changing rate, gear selection, driving speed and driving acceleration are key factors for fuel economy.
- 2) The driver-bus-route evaluation index ($l_{D_V_R}$) was proposed and the calculation method was illustrated in detail. The calibrated evaluation index can be used to predict driver-bus-route evaluation index of other bus line. It can be used to sort better driver-bus-route arrangements to improve fuel economy for bus companies.
- 3) The larger evaluation index $l_{D_V_R}$ demonstrated the higher fuel consumption, and vice versa.

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