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Space Optimization of Speed Guidance Control on Urban Expressway

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Abstract

Urban expressway plays an important role in the urban road network. It is gradually shifting from large-scale infrastructure-oriented to refinement of traffic management. In order to improve the efficiency and safety of urban expressway, macroscopic dynamic traffic flow model is extended under speed guidance control. Multi-objective optimization model is established based on the total travel time of vehicles and the value of speed guidance changes. Three scenarios are carried out with Strength Pareto Evolutionary Algorithm. The optimal scenario is adopted based on set theory then the best solution is determined. Simulation analysis is carried out in simulation platform under the optimal solution. The results show that speed guidance control has a good effect to smooth traffic flow, alleviate traffic congestion and improve traffic safety which can be applied in practice to provide a theoretical support for active traffic management.

Keywords: *traffic management; urban expressway; speed guidance control; multi-objective optimization*

1. Introduction

As the backbone of the city road network, urban expressway shares large proportion of the traffic. In Beijing, major urban expressway accounts for only 8% of the total length, but carries nearly 50% of the traffic flow [1]; in Shanghai, only 5% bears more than 35% of the city traffic traveling. Urban expressway plays a vital role in the urban road network which gradually shifted from the large-scale infrastructure construction to refinement traffic management. The first known experiments with variable speed limit signs took place on a 30 km stretch of German motorway A8 between Munich and the border city of Salzburg, Austria. Mechanically variable message signs could display speeds of 60, 80 and 100 km/h. Personnel monitored traffic using video technology, and manually controlled the signage. In 2009, 1,300 km of German motorways were equipped with variable speed limits systems. More typically, variable speed limits are used on remote stretches of highway in the United States in areas with extreme changes in driving conditions. As a response to fog-induced chain-reaction collisions involving 99 vehicles in 1990, a variable speed limit system covering 19 miles of Interstate 75 in Tennessee was implemented in fog-prone areas around the Hiwassee River. A variable speed limit was introduced on part of Britain's M25 motorway. Initial results suggested savings in journey times, smoother-flowing traffic, as well as a fall in the number of crashes. However a 2004 national audit organization report noted that the business case was unproved; conditions at the site of the Variable Speed Limits trial were not stable before or during the trial, and the study was deemed neither properly controlled nor reliable.

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In an actual variable speed limit system, speed limits vary strategically and periodically in accordance with traffic volume and weather conditions to achieve better safety, efficiency, and environmental sustainability on urban expressway. Speed and speed variance of vehicles are important factors related to safety, especially during severe weather conditions. According to the earlier variable speed limits studies, drivers generally choose the driving speed among the range, which is essentially a method of wide range speed control.

2. Dynamic Traffic Flow Model

Control-oriented macro dynamic traffic flow model describes the relationship among traffic flow over space and time even traffic control variables. LW model was proposed by British scholar Lighthill and Whitham in 1955. Against the defects, Payne proposed dynamic relationship between speed and density [2]. The model was further extended considering off-ramp, on-ramp and lane change factors by Papageorgiou [3, 4]. Model proposed by Payne and Papageorgiou are widely used in practice [5, 6]. Scholars between domestic and foreign have also proposed various models which are mostly around dynamic relationship between speed and density [7, 8]. Second order dynamic METANET model is used to describe the traffic flow. To make the calculated optimal speed guidance value more realistic and accurate, dynamic traffic flow model are described as eq. (1) and eq. (2):

$$\rho_i(k+1)=\rho_i(k)+\frac{T}{L_i\lambda_i}(\rho_{i-1}(k)v_{i-1}(k)-\rho_i(k)v_i(k)+r_i(k)-s_i(k)) \tag{1}$$

$$v_i(k+1)=v_i(k)+\frac{T}{\tau}(u_i(k)-v_i(k))+\frac{T}{L_i}v_i(k)(v_{i-1}(k)-v_i(k)) -\frac{1}{\tau}\left(\frac{\nu T}{L_i}\frac{\rho_{i+1}(k)-\rho_i(k)}{\rho_i(k)+\kappa}\right) \tag{2}$$

Where i is road segment index, k is time interval index, T is the time step used for data collection, L_i is length of road segment. τ, ν, κ are the model parameters, τ is a time constant, ν is the anticipation constant and κ is model parameters which are equal at a segment. $\rho_i(k)$ is the traffic density of road segment i at time index k , $v_i(k)$ is the mean speed of road segment i at time index k , $r_i(k)$ is the metering flow rate of road segment i at time index k , $s_i(k)$ is the total off-ramp flow rate of road segment i at time index k , $u_i(k)$ is the desired control speed of road segment i at time index k and λ_i is the number of lanes of road segments.

The paper determines the origins flow and speed parameters of upstream mainline by the ramp length of queue of upstream cell segment. The models are listed as eq. (3) to eq. (5):

$$w_0(k+1)=w_0(k)+T(d_0(k)-q_0(k)) \tag{3}$$

$$q_0(k)=\min\left[d_0(k)+w_0(k)/T, Q_0\frac{\rho_{\max}-\rho_{\mu,1}(k)}{\rho_{\max}-\rho_{crit,\mu}}\right] \tag{4}$$

$$v = \min\left[(1+\alpha) v_{crit,m}(k), v_{free} \exp[-\frac{1}{\alpha m}(\frac{\rho_{\mu,1}(k)}{\rho_{crit,u}})^{\alpha m}] \right] \tag{5}$$

Where Q_0 is the onramp flow capacity, $\rho_{\max}$ is the maximum density of onramp, $\rho_{crit,\mu}$ is the critical density of onramp at which the traffic flow becomes unstable, $\rho_{\mu,1}(k)$ is the density of mainline which segment the onramp linked, $v_{crit,m}$ is the critical speed of mainline at which the traffic flow becomes unstable, v_{free} is the speed of freely traffic flow, $w_0(k)$ is the maximum number of vehicles stored in onramp and $d_0(k)$ is the onramp demand flow.

Based on consideration of traffic safety, the speed change should be smooth temporally and spatially. So the control speed variation should be less than 10 km/h over time and distance interval, the following constraints are adopted in eq. (6):

$$\bar{V}_{\min} \le u_i(k) \le \bar{V}_{\max} \tag{6}$$

Where $\bar{V}_{\min}$ and $\bar{V}_{\max}$ are the minimum and maximum control speed for speed guidance control respectively, $\bar{V}_{\min}$ taken as 20 km/h and $\bar{V}_{\max}$ taken as 80 km/h.

3. Model Parameter Calibration

Inner ring expressway in Shanghai was selected as the research object. It was four km long and divided into eight sections. Traffic parameters detectors located downstream and upstream the expressway. Simulation model was established, calibration and verification. Function Lsqnonlin() in the MATLAB software was used to realize the calibration of macro traffic flow parameters [9]. The initial parameter values of the macro dynamic traffic flow model are list in Table 1. The results of calibration and simulation were shown in Table 2 and Table 3. Parameter combinations in case 1 were selected as the model basic parameters.

Table 1. Initial Parameter Values of the Macro Dynamic Traffic Flow Model

Model parameters	Initial parameter values	Model parameters	Initial parameter values
d_0	2000veh/h	T	20s
w_0	12veh/lane	$\rho_{u,1}$	35 veh/km/lane
$\rho_{\max}$	120veh/km/lane	v_{free}	70km/h
$\rho_{crit,u}$	38 veh/km/lane	$v_{crit,m}$	45km/h
Q_0	1800 veh/h	α	0.05

Table 2. Results of Parameter Calibration

τ/ (h)	ν/ (km^2/h)	k /(veh/km)
0.01	9	34
0.01	7	26
0.015	11	24
0.015	12	31
0.02	10	35
0.02	8	26
0.015	13	28
0.015	9	30

Table 3. Simulation Results of the Evaluation

Case	The speed average relative error (%)	The flow average relative error (%)
1	8.34	8.43
2	6.67	15.68
3	8.96	54.73
4	12.82	12.98
5	20.80	7.78
6	34.22	21.30

4. Multi-objective Optimization

When the speed guidance control used in the traffic management, changes of speed values not only take into account its nearest traffic flow but also need to take into account traffic conditions downstream and even upstream. In the actual control, considering more extensive road sections traffic, the control system would be more complex. It should be find a balance between efficiency and benefits. v_0 and ρ_0 were the initial velocity and the density value, $v_i(k)$ and $\rho_i(k)$ were the velocity and the density value about road section i at k interval. Then changes of speed guidance values $\Delta sg_i(k)$ are determined by the following from eq. (9) to eq. (13):

$$\Delta sg_i(k) = [\theta_{1,} \cdots \theta_n] v(k) + [\varphi_{1,} \cdots \varphi_n] \rho(k) \tag{9}$$

$$v(k) = [\Delta v_{i-n_u}(k), \cdots, \Delta v_i(k) \cdots, \Delta v_{i+n_d}(k)] \tag{10}$$

$$\rho(k) = [\Delta \rho_{i-n_u}(k), \cdots, \Delta \rho_i(k) \cdots, \Delta \rho_{i+n_d}(k)] \tag{11}$$

$$\Delta v_i(k) = v_i(k) - v_0 \tag{12}$$

$$\Delta \rho_i(k) = \rho_i(k) - \rho_0 \tag{13}$$

The basic principles of the optimization objective function are to establish a balance between efficiency and safety. Objective function J_{TTS} is the total travel time and J_{SG} is the total changes of speed guidance values shown in eq. (14) and eq. (15).

$$J_{TTS} = T_1 \sum_{k=1}^{k_{sim}} \left(\sum_{i=1}^{N} \rho_i(k) L_i \lambda_i + w_i(k) \right) \tag{14}$$

$$J_{SG} = T_2 \sum_{k'=1}^{k'_{sim}} \sum_{i=1}^{N} \left(sg_i(k') - sg_i(k'-1) \right) \tag{15}$$

Where T_1 and k_{sim} are the macro-dynamic traffic flow sampling period and time interval, respectively. T_2 and k'_{sim} are the period of speed guidance change and time interval, respectively.

As one of the mature multi-objective genetic algorithms, Strength pareto evolutionary algorithm has the ability of operation faster, stronger stability and relative dispersion solution [10-13]. Though there are several Pareto optimal solutions, no better or worse between Pareto optimal solutions. According to the degree of importance on each goal, the solution is selected from the Pareto solution sets. An optimal solution among the multi-objective optimization Pareto sets need to be selected for the speed guidance control of urban freeway based on set theory optimal methods shown in eq. (16) and eq. (17).

$$\mu_i = \begin{cases} 1, & F_i \le F_i^{\min} \\ \dfrac{F_i^{\max} - F_i}{F_i^{\max} - F_i^{\min}}, & F_i^{\min} < F_i < F_i^{\max} \\ 0, & F_i \ge F_i^{\max} \end{cases} \tag{16}$$

$F_i^{\max}$ and $F_i^{\min}$ are the minimum and maximum optimization goals, respectively. F_i is the optimization goal.

$$\mu^k = \frac{\sum_{i=1}^{N_{obj}} \mu_i^k}{\sum_{i=1}^{N_{obj}} \sum_{j=1}^{M} \mu_i^j} \tag{17}$$

M is the number of solutions in the Pareto set, N_{obj} is the number of optimization targets.

According to the Pareto set that was in descending order by μ^k , the solution with the maximum value was set as the Pareto optimal solution.

5. Surrogate Safety Assessment Model [14]

In the speed guidance control online simulation system, vissim software is used to simulate the real world traffic. The macro dynamic traffic flow model is established in matlab software. Data and control strategies were exchange through the API interface among vb.net, vissim and matlab. According to the functional orientation, online simulation system was divided into four modules: simulation module, strategy module, interface module and database module. Road safety assessment can be divided into direct and indirect methods. Direct assessment method was based on accident statistics which was widely used in road traffic management. Though the method was simple to operate, it also had some disadvantages, such as relatively small of the road traffic accidents data, relatively long of the statistical period, great randomness of the accident and other problems. Traffic conflict technique is the representative method of the indirect traffic safety evaluation which has obvious advantages, relatively large number of conflict, short period and strong regularity. It was extremely widely applied in the field of road traffic safety. However, traffic conflict observed manually always was arbitrary, taking a lot of manpower and resources. Therefore surrogate safety assessment model which was developed by the United States Federal Highway Administration was used to analyze micro-simulation model output trajectory file. SSAM employed the simulation method to analyze the security.

Figure 1 illustrates the definitions of the surrogate measures for a conflict line during a rear-end event. Rear-end events describe those conflict lines that occur specifically when the two interacting vehicles are already in the same lane. As shown in Figure 1, TTC is defined at each time step during the conflict line event. This begins when vehicle A begins braking to avoid the collision. At each time step, calculate the time that it would take vehicle A to reach the current location of vehicle B if its velocity remained unchanged from the start of the time period. The minimum of these TTC values is recorded as the TTC for the conflict line event. If the TTC values begin to increase after the first TTC calculation, the first value will be the minimum. If the TTC values begin to decrease, the values must continue to be calculated until they begin to increase. The value at the inflection point is the minimum TTC. If the TTC values begin to decrease and continue to decrease until the leader vehicle leaves the roadway or a maximum reference distance is reached, the minimum TTC value is recorded as the TTC value at the end of the conflict line event. Similar to the TTC, the PET must be recorded as the minimum PET over the conflict line duration. Two PET values are illustrated in Figure 1. At each time step, the location of the leading vehicle must be recorded until the vehicles are no longer on a collision course (speed of vehicle B has dropped to zero) or the maximum conflict distance has been reached or the leading vehicle leaves the lane of the following vehicle. For each location recorded for the leading vehicle, the PET is calculated as the time difference between the arrival of the leading vehicle at that location and the arrival of the following vehicle at that location. The minimum PET is then selected from the PETs calculated for each location as the PET recorded for this conflict line event. For the situation shown in Figure 1, the minimum PET that would be recorded is PET-1. Similar to the conflict points, MaxS is first defined for each vehicle independently as the maximum speed of the vehicle between the times t1 and t9 (or the time when the vehicles are no longer on a collision course). Then the maximum of the two maximum values for each vehicle is recorded as the MaxS value for the conflict line event. Surrogate safety measures from traffic simulation models identical to the calculation for DeltaS in the conflict point events, the DeltaS for the conflict line events is first defined for each time slice (from the beginning to the end of the conflict event) as the difference between the velocity of the two conflicting vehicles. Then the maximum of those DeltaS values for each time slice would be recorded as the DeltaS value. Initial Deceleration Rate The initial DR is the second derivative of curve B (following vehicle) at time t2. It should be a state variable storedby the simulation model and directly available to be recorded. Noting the latitude and longitude of the starting and ending points of the conflict line event can indicate particular locations that are risk areas. Where the conflict stops could be a number of points in the time line. For simplicity, we choose the ending point as the location of the following vehicle where the minimum PET is recorded. The beginning location is the starting point of the encroachment. The resulting line represents the risk area of the conflict occurrence.

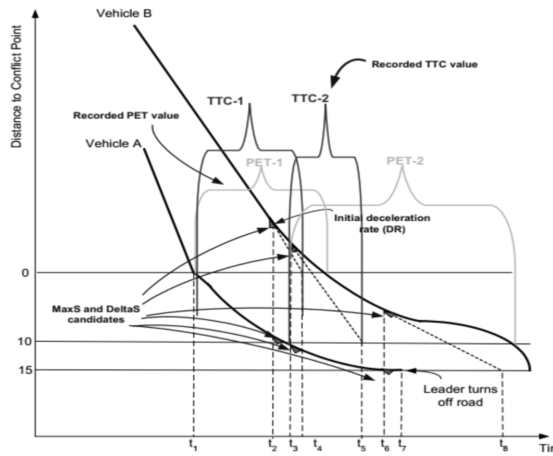

Figure 1. Surrogates Identified on Rear-end Line Diagram

6. Simulation Analysis and Results

The urban expressway used in simulation is 4 km, dividing into 8 segments and each 500 meters. The expressway is two-lane, capacity is 2000veh/h/lane and entrance traffic demand is 3800veh/h. Each segment initial density is 27veh/km/lane and initial speed is 70km / h. The value of initial speed guidance control is 80km/h; the total simulation period is 90 minutes. In order to simplify the calculation, on or off the ramp flow is zero. The eighth segment is utilized to simulate traffic flow mutation.

The sampling period of the macroscopic dynamic traffic flow models is 10 seconds, speed guide values change cycle is 60 seconds and the speed impact of changes in the lag time of 18 seconds. For the parameters in the SPEA2 algorithm, the population is 50, evolution generations are 200, crossover probability is 0.8 and mutation probability is 0.01. Three simulation programs were designed for comparative analysis. In the first program, the speed guidance value is only determined by the nearest traffic flow. In the second program, the value is also influenced by the downstream traffic flow. Changes of speed guidance was showed in Figure 2. Both upstream and downstream have the effect on speed guidance value in the third program.

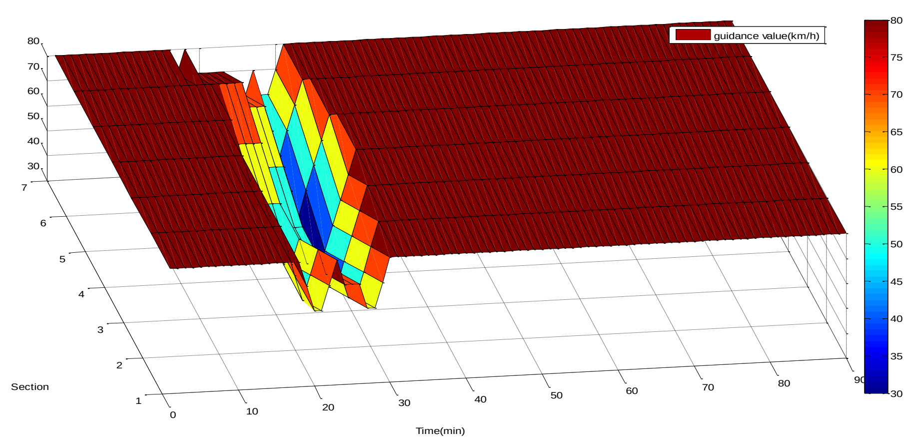

Figure 2. Changes of Speed Guidance

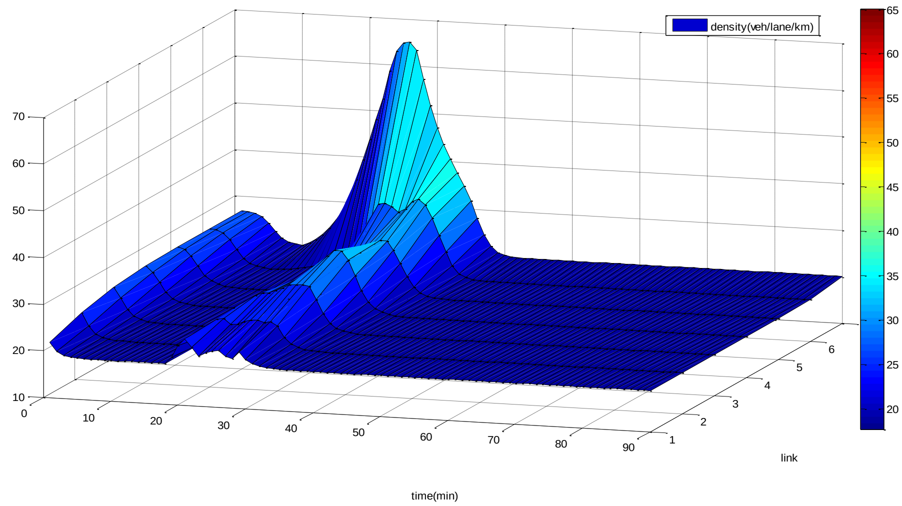

Figure 3. Changes of Density

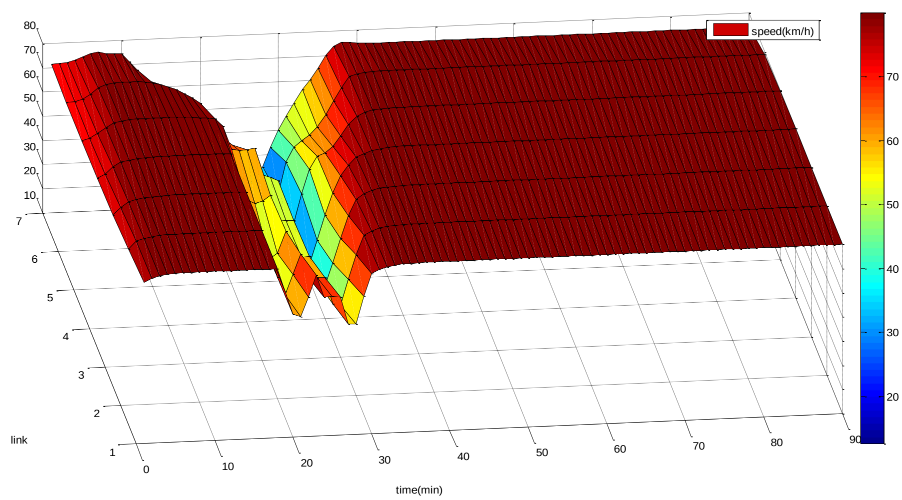

Figure 4. Changes of Speed

After sorting based on set theory, 30 Pareto frontiers are taking into analysis. When the downstream traffic was taking into account, the objective function performance has been significantly improved. But the objective function did not significantly optimized when much more downstream sections traffic were involved. Changes of speed and density were showed in Figure 3 and Figure 4. Comparing to scenario 2, total traveling time increase 9% and changes of speed guidance reduce 30%. In scenario 3, though the speed guidance value change reduced by 50%, the total time-consuming was significantly increased by 25%. To balance between efficiency and safety, scenario 2 was selected in the control strategy of speed guidance simulation.

When short-term traffic mutation appearing, blocking propagated upstream and has a long duration. Traffic got a better smoothing under speed guidance control which means traffic interference had been effectively suppressed. As can be seen from the simulation results, the traffic can better control, both road safety and operational efficiency has been improved.

7. Conclusion

The macroscopic traffic flow parameters characteristic is an important research content in traffic flow theory. Depending on the real traffic flow data on typical parts, dynamic characteristic of traffic flow was analyzes, several traffic flow parameters for urban expressway were summarizes. Then the characteristic variables of the expressway traffic flow were identified which support meticulous management for urban expressway. In order to improve the efficiency of urban expressway and security levels, based on the speed of the boot under the control of the role of urban freeway traffic flow model, a multi-objective to spend time with gross vehicle speed change range values guiding objective optimization model; Strength Pareto evolutionary algorithm uses to solve, but based on set theory to select the optimal solution from the Pareto frontier. Values at different speeds to determine the program guide application matlab simulation analysis and established the optimal control scheme. Simulation results show that the speed of the boot for ease congestion control has a good effect to improve traffic safety, traffic management applications to proactively providing a theoretical basis in the fast path. The result can provide scientific basis for the design, layout, operation, management and evaluation of urban expressway. Optimal solution for variable speed limit values established in other traffic situations under adaptability requires further study.

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References

[1] D. H. Wang, X. W. Chen and S. H. Yang, “Analysis of Traffic Bottleneck on Beijing Urban Expressway”, Proceedings of 7th International Conference of Chinese Transportation Professionals, **(2007)** August 2-5; Beijing.
[2] C. Fuhs, “Synthesis of Active Traffic Management Experiences in Europe and the United States”, **(2010)**; Washington, D. C.: Federal Highway Administration.
[3] A. Hegyi, D. Schutter, and H.Hellendoorn, “Optimal Coordination of Variable Speed Limits to Suppress Shock Waves”, Transportation Research Record, vol. 1852, no.1, **(2004)**, pp.167-274.
[4] A. Hegyi, D. Schutter, and H. Hellendoorn, “Model Predictive Control for Optimal Coordination of Ramp Metering and Variable Speed Limits”, Transportation Research Part C, vol. 13, **(2005)**, pp.185-209.
[5] M. J. Lighthill, and G. B.Whitham, “On Kinematic Waves II: A Traffic Flow Theory on Long Crowded Roads”, Proceedings of the Royal Society of London, vol. 229, **(1955)**, pp. 317-345.
[6] H. J. Payne, “Models of Freeway Traffic and Control”, Simulation Council Proceedings, vol. 1, no.1, **(1971)**, pp. 51-61.
[7] M. Papageorgiou, “Macroscopic Modeling of Traffic Flow on the Boulevard Paripherique in Paris”, Transportation Research Part B, vol. 23, no.1, **(1989)**, pp. 29-34.
[8] M. Papageorgiou and J. M.Blosseville, “Modeling and Real-Time Control of Traffic Flow on the Southern Part of Boulevard Peripherique in Paris”, Transportation Research Part A, vol. 24, no.5, **(1990)**, pp. 345-359.
[9] H. C. Gan, L. J. Sun and Y. Hao, “A Case Study of Urban Expressway Traffic Flow Based on Hig-order Continuum Model”, Journal of Tongji University :Natural Science, vol. 35, no.5, **(2007)**, pp. 602-606.
[10] E. Zitzler, M. Laumanns and L. Theile, “SPEA2: Improving the Strength Pareto Evolutionary Algorithm for Multi-Objective Optimization”, **(2001)**, Swiss Federal Institute of Technology.
[11] E. Zitzler, M. Laumanns and L. Theile, “SPEA2: Improving the Strength Pareto Evolutionary Algorithm for Multi-Objective Optimization”, Proceedings of Evolutionary Methods for Design, Optimization and Control, **(2002)** October 12-15; Barcelona, Spain.

[12] A. Abido, "Multi-Objective Evolutionary Algorithms for Electric Power Dispatch Problem" , IEEE Transactions on Evolutionary Computation, vol. 10, no.3, **(2006)**, pp. 315-329.
[13] Z. K. Li, J. R. Tian and Y. X. Feng, "Multi-Objective Injecting Performances Optimization of Injection Molding Machinery Based on Strength Pareto Evolutionary Algorithm", Computer Integrated Manufacturing Systems, vol. 13, no.11, **(2007)**, pp. 2162-2168.
[14] D. Gettman and L. Head, "Surrogate safety measures from traffic simulation models", **(2003)**; Washington DC: Siemens Gardner Transportation Systems.

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