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Research Article

Travel Distance on Each Grade Road of Urban City Based on Reliability

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In order to reflect influence of travel time reliability on route choosing, considering traffic accidents' influence under random state, we analyzed travel distance distribution regularity of each grade road, through traffic assignment. Travel time reliability model was produced and modified, considering the randomness of accidents, delay time, and capacity. The maximum preponderant travel range of each grade road was defined, and stochastic user equilibrium assignment was adopted to get travel turnover and distance, based on the corrected model. And then regulation of distance distribution was analyzed. Conclusion shows that reasonable travel distance of local way, distribution way, and primary way is 1 km, 2.28 km, and 3.54 km, respectively.

1. Introduction

Traditional research of travel distance was generally based on ideal environment. Investigation and statistical analysis have been applied to study the route choice of traveler and then deduce the travel distance. With the surge in the number of motor vehicles, traffic congestion is always caused by accidents; therefore the reliability of road network is particularly important. Under the principle, research on route choice is different from the traditional study, and travel distance on each grade road is also changed significantly.

The current study proposed some methods of travel distance from different perspective. Love and Morris [1] evaluated the accuracy of a range of reasonable forms for distance estimating functions using samples of urban and rural road distances. Alpaydin et al. [2] proposed to use nonparametric approaches using neural networks for estimating actual distances. Brimberg and Love [3] and Ballou et al. [4] estimated the travel distance from the weighted one-two norm and circuity factors, respectively. Schlossberg et al. [5] examined the relationship between urban form, distance, and middle school students walking and biking to and from four schools in Oregon. Golob and van Wissen [6] proposed a dynamic simultaneous equations model of car ownership and modal travel distances. Zhang et al. [7] find that travel distance of tourists to a destination is related to their demographic data, but is not related to the tourist motivation.

In China, Zhou et al. [8] discussed the distance distribution regularity, according to the function and characteristic of each grade road. The above study did not consider the actual traffic situation and travel time reliability but only took the ideal road network and travel environment into account.

In respect of time reliability, Chen et al. [9] presented a degraded time reliability model considering the influence of weather, congestion, and accidents. Clark and Watling [10] proposed a technique for estimating the probability distribution of total network travel time, in light of normal day-to-day variations in the travel demand matrix over a road traffic network. From the above, network reliability affects traveler's route choice, and travel distance is of major difference from the past, under the premise of satisfying travel demand.

However, in the current research of travel time reliability, almost study took traffic capacity as indicator, rarely considering traffic accidents. This paper defines the maximum travel distance according to the characteristic of auto-vehicle trip. Then, incorporate traffic accidents into trip time reliability model, and take this as the basis of route choice. After the traffic assignment, analyze travel distance of each grade road and the regularity.

2. Research Procedures

(1) Build original network and define the maximum travel distance of each grade road and traffic assignment network.

(2) Construct travel time reliability function $R(x)$, and study the results of traffic assignment, taking the maximum $R(x)$ as target.

(3) Compare the travel distance under different networks, and get the maximum distance of each grade road.

(4) According to the minimum and maximum travel distance, deduce the distribution regularity of travel distance.

3. Network Constructions

3.1. Origin Network. Suppose that road network is regular grid. The grade of road is descending by one grade, and higher roads encompass some lower roads. The space between same grade roads in east-west direction is the same as south-north direction. Travelers should first go by high grade roads and then lower grade roads, conversely from lower roads to higher roads. Step over is forbidden.

According to "*Urban road traffic planning and design specifications*" [11] (GB50220-95), density of express way, primary roads, distribution roads, and local roads in major city is 0.4~0.5 km/km^2, 0.8~1.2 km/km^2, 1.2~1.4 km/km^2, and 3~4 km/km^2, respectively. Suppose that the average distance between roads with grade i is d_i ($i = 1$ means local road, $i = 2$ means distribution road, $i = 3$ means primary road, and $i = 4$ means express way). In accordance with the specifications for roads space, the origin road network is shown as Figure 1.

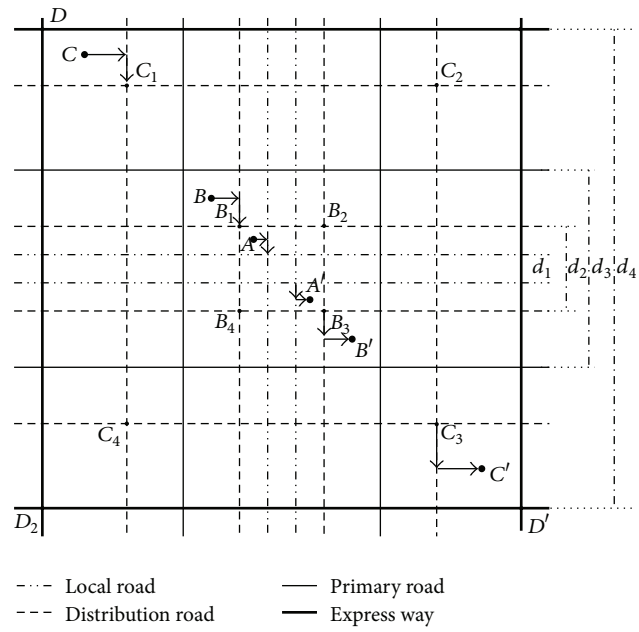

Figure 1: Origin network.

3.2. Maximum Preponderant Travel Distance. Obviously, possible travel distance for each grade road is infinite. However, considering the convenience, preponderance for road with grade i will not exist, if roads with grade higher than i exist in the network. That is, roads of grade i cannot be considered as the highest grade roads which travelers go through. Therefore, preponderant travel distance of road with grade i means that, in the range covered by road with grade $i + 1$, traveler's trip distance which the highest grade road travelers can go by is i. That is diagonal trip among the range covered by road with grade $i + 1$.

For local roads, the maximum preponderant travel should be the diagonal trip among the range covered by distribution roads, which is shown as trip between node A and node A' in Figure 1 (nodes A and A' are located in the center, the same as below). Similarly, maximum preponderant travel of distribution roads, primary roads, and express ways is corresponding to node B and node B', node C and node C', and node D and node D'.

3.3. Road Network Construction for Traffic Assignment. As shown in Figure 1, for the maximum travel range of local roads, trip distance between nodes A and A' is $D_1 = 2d_1 + (d_2 - d_1)/2$, no matter which route travelers choose. Supposing that the traffic in OD is q_1, then turnover for local roads is $Q_1^{A,A'} = q_1 D_1 = q_1 * (2d_1 + (d_2 - d_1)/2)$.

For the maximum travel range of distribution roads, travel from node B to B' can be decomposed into three stages, concluding travel from node B to B_1, travel among the range covered by node $B_1B_2B_3B_4$, and travel from node B_3 to B'. Supposing that OD traffic between nodes B and B' is q_2, turnover of distribution roads from node B to $B_1 Q_2^{B,B_1}$ and node B_3 to $B' Q_2^{B_3,B'}$ is $Q_2^{B,B_1} = Q_2^{B_3,B'} = q_2 * (d_3 - d_2)/4$. Turnover of other grade roads from node B_1 to B_3 can be got by traffic assignment among the network covered by nodes B_1, B_2, B_3, and B_4.

For the maximum travel range of primary roads, travel from node C to C' can be decomposed into three stages, concluding travel from node C to C_1, travel among the range covered by node $C_1C_2C_3C_4$, and travel from node C_3 to C'. Supposing that OD traffic between nodes C and C' is q_3, turnover of distribution roads from node C to $C_1 Q_2^{C,C_1}$ and node C_3 to $C' Q_2^{C_3,C'}$ is $Q_2^{C,C_1} = Q_2^{C_3,C'} = q_3 * ((d_4 - d_3)/2 - (d_3 - d_2)/2)/2$. Turnover of other grade roads from node C_1 to C_3 can be got by traffic assignment among the network covered by nodes C_1, C_2, C_3, and C_4.

For express way, travel space can be viewed as the range covered by nodes D and D' (i.e., the whole network).

Based on what is mentioned above, traffic assignment should only be adopted on the area of $B_1B_2B_3B_4$, $C_1C_2C_3C_4$, and $DD_1D'D_2$. Then, travel turnover on maximum travel range of each grade road can be got.

4. Reliability of Trip Time

4.1. Reliability of Trip Time. When choosing travel route, travelers pay close attention to trip time. However, trip time is related to road condition, but also the reliability of network. Particularly, with the augment of vehicles, congestion caused by traffic accidents frequently occurs. Therefore, traffic accidents are introduced to the reliability model.

Reliability of trip time describes the probability of road keeping unimpeded. Introducing the saturation and expectation, model of trip time reliability can be described as follows [12]:

$$R(x) = \exp\left(h - \frac{a}{2\sqrt{1-v/c}\left(1+\sqrt{1-v/c}\right)}\right), \quad (1)$$

in which h means roads' condition, that is, the factors influencing road reliability except traffic state. Maximum value of h is $a/4$, and at this moment trip time reliability is only influenced by traffic state.

Parameter a reflects traveler's expectation. Higher expectation means larger a. Consider $a = t_0/E(t)$. t_0 indicates travel time under free flow, and $E(t)$ indicates expectation travel time. Generally, $E(t)$ is the minimum travel time in all trip routes between OD pairs under free flow, that is, $E(t) = \{\min(t_0^i, i \in \text{net}\}$. t_0^i means the free travel time for route i.

v/c means the saturation of the road.

4.2. Probability of Accidents. Supposing that accidents are event M, and congestion is event N, then probability of congestion caused by traffic accidents is $P(NM) = P(N \mid M) \cdot P(M)$, in which $P(N \mid M)$ means probability of congestion if traffic accidents are occurring and $P(M)$ means probability of traffic accidents.

Traffic accidents are random and can be seen as obeying normal distribution. Supposing that x is the number of traffic accidents, u_1 and ${\sigma_1}^2$ are average and variance values of the traffic accidents, respectively. Probability density function $f(x)$ can be described as

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma_1} e^{-(x-u_1)^2/2{\sigma_1}^2} \quad x > 0. \quad (2)$$

Supposing that k is forecast value of traffic accidents (number/year), then $u_1 = k$. According to probability statistics theory, standard variance can be seen as one-third of difference between average and minimum values [13]; then $\sigma_1 = (u_1 - \min(x))/3 = u_1/3 = k/3$. Probability density function $f(x)$ can be described as

$$f(x) = \frac{1}{\sqrt{2\pi} \times (u_1/3)} e^{W_1} = \frac{1}{\sqrt{2\pi} \times (k/3)} e^{W_2}, \quad x \geq 0, \quad (3)$$

in which $W_1 = -9(x-u_1)^2/(2\times {u_1}^2)$, $W_2 = -9(x-k)^2/(2\times k^2)$.

Probability of traffic accidents is $P(A) = P(x > 0) = 1 - P(x = 0) = 1 - f(0) = 1 - (3/\sqrt{2\pi}k)e^{-4.5}$.

The number of accidents is related to traffic flow and road characteristics. For road section, $k_1 = \alpha_1 d^{\beta_1} q^{\gamma_1}$, in which d means length of road section (km), q means traffic flow (pcu·year^{-1}), and α_1, β_1, and γ_1 are parameters. According to Sawalha and Sayed [14], $\alpha_1 = 0.0035$, $\beta_1 = 0.6724$, and $\gamma_1 = 0.9679$. For intersection, $k_2 = \alpha_2 F_1^{\beta_2} F_2^{\gamma_2}$, in which F_1 means traffic flow on primary road (pcu·year^{-1}), F_2 means traffic flow on minor road (pcu·year^{-1}), and α_2, β_2, and γ_2 are parameters $\alpha_2 = 1.08 \times 10^{-4}$, $\beta_2 = 0.53$, and $\gamma_2 = 0.52$ [15].

For road $m-n$, defining total traffic accidents as the traffic accidents sum of section and intersection, then $k = k_1 + k_2$.

4.3. Probability of Congestion Caused by Traffic Accidents. Assume that, after traffic accidents, road capacity is decreased to C (pcu·h^{-1}). At this moment, traffic flow is q (pcu·h^{-1}) and congestion probability $P(N \mid M)$ is

$$P(N \mid M) = \begin{cases} 1, & C < q \\ 0, & C \geq q. \end{cases} \quad (4)$$

Probability of congestion caused by accidents $P(NM)$ is

$$P(NM) = P(N \mid M) \cdot P(M) = \begin{cases} 1 - \dfrac{3}{\sqrt{2\pi}k} e^{-4.5}, & C < q \\ 0, & C \geq q. \end{cases} \quad (5)$$

Therefore, probability of normal traffic flow is $(1 - P(NM))$. When traffic accidents are taken into consideration, $h = a/4 * (1 - P(NM))$. Function of travel time reliability can be described as

$$\begin{aligned} R(m,n) &= \exp\left(\frac{a}{4}(1 - P(NM)) - \frac{a}{2\sqrt{1-v/c}\left(1+\sqrt{1-v/c}\right)}\right) \\ &= \begin{cases} \exp\left(\dfrac{1}{4}\left(\dfrac{t_0^{m,n}}{\min\{t_0^i, i \in \text{net}\}}\right)\left(\dfrac{3}{\sqrt{2\pi}k}e^{-4.5}\right) - \dfrac{t_0^{m,n}/\min\{t_0^i, i \in \text{net}\}}{2\sqrt{1-q/C}\left(1+\sqrt{1-q/C}\right)}\right), & C < q, \\ \exp\left(\dfrac{1}{4}\left(\dfrac{t_0^{m,n}}{\min\{t_0^i, i \in \text{net}\}}\right) - \dfrac{t_0^{m,n}/\min\{t_0^i, i \in \text{net}\}}{2\sqrt{1-q/C}\left(1+\sqrt{1-q/C}\right)}\right), & C < q. \end{cases} \end{aligned} \quad (6)$$

In 1996, *traffic control system manual* of FHWA put forward the capacity influence of urgency accidents, as shown in Table 1 [16].

Table 1: Valid traffic capacity percentage under accidents.

Lanes in one way	Lanes of congestion		
	1	2	3
2	0.35	0	/
3	0.49	0.17	0
4	0.58	0.25	0.13

Generally, lane occupied by traffic accidents is one, and then capacity after accidents should be viewed as normal capacity multiplied by percentage corresponding to total lanes and lane of congestion in Table 1. For example, normal capacity of distribution way for 4 lanes in both ways is 1185 pcu/h and average capacity after accidents is $C = 1185 * 0.35 = 415$ pcu/h.

Travel time reliability model not only reflects the expectation of travel time, but also influences the congestion caused by accidents. Then, the amended model considers comprehensive factor when choosing trip route. Travel time reliability of one route is product of all road sections; that is,

$$R_{\text{route}j} = \prod_{i=1}^{n_j} R_i. \tag{7}$$

5. Travel Distance Distribution

5.1. Traffic Assignment. Traffic assignment should be adopted on the maximum travel range of distribution way $B_1B_2B_3B_4$, primary way $C_1C_2C_3C_4$, and express way $DD_1D'D_2$, through which we can obtain the maximum travel distance. In traffic assignment, suppose the origin and destination nodes are top left corner and bottom right corner, respectively. Suppose that OD volume is q_2, q_3, and q_4 for the above three assignment networks.

Stochastic user equilibrium assignment is applied in traffic assignment, and principle of route choosing is reliability maximization. That is, for routes collection $[R_{\text{OD}}]$, if route r satisfies

$R_{\text{route}r} = \max(R_{\text{route}j}, j \in [R]_{\text{OD}})$, then travelers will choose route r.

(1) For network A–A', travel turnover of local ways is $Q_1^{A,A'} = q_1D_1 = q_1 * (2d_1 + (d_2 - d_1)/2)$, and travel distance is $L_1^{A,A'} = q_1D_1/q_1 = 2d_1 + (d_2 - d_1)/2$.

(2) For network $B_1B_2B_3B_4$, suppose that traffic turnovers of local and distribution ways through assignment are $Q_1^{B_1,B_3}$, $Q_2^{B_1,B_3}$. Among the range node B–B', turnover of local ways is $Q_1^{B,B'} = Q_1^{B_1,B_3}$, and travel distance is $L_1^{B,B'} = Q_1^{B_1,B_3}/q_2$. Travel turnover of distribution ways is $Q_2^{B,B'} = Q_2^{B,B_1} + Q_2^{B_1,B_3} + Q_2^{B_3,B'} = 2q_2 * (d_3 - d_2)/4 + Q_2^{B_1,B_3}$, and travel distance is $L_2^{B,B'} = Q_2^{B,B'}/q_2 = 2(d_3 - d_2)/4 + Q_2^{B_1,B_3}/q_2$.

(3) For network $C_1C_2C_3C_4$, suppose that traffic turnovers of distribution and primary ways through assignment are $Q_2^{C_1,C_3}$, $Q_3^{C_1,C_3}$. Among the range node C–C', turnover of distribution ways is $Q_2^{C_1,C_3} = Q_2^{C,C_1} + Q_2^{C_1,C_3} + Q_2^{C_3,C'} = 2q_3 * ((d_4 - d_3)/2 - (d_3 - d_2)/2)/2 + Q_2^{C_1,C_3}$, and travel distance is $L_2^{C,C'} = Q_2^{C,C'}/q_3 = (d_4 - d_3)/2 - (d_3 - d_2)/2 + Q_2^{C_1,C_3}/q_3$. Turnover of primary ways is $Q_3^{C,C'} = Q_3^{C_1,C_3}$, and travel distance is $L_3^{C,C'} = Q_3^{C_1,C_3}/q_3$.

(4) For network $DD_1D'D_2$, suppose that traffic turnovers of distribution, primary, and express ways through assignment are $Q_2^{D,D'}$, $Q_3^{D,D'}$, and $Q_4^{D,D'}$. Then, among the range node D–D', travel distance for each grade road is $L_2^{D,D'} = Q_2^{D,D'}/q_4$, $L_3^{D,D'} = Q_3^{D,D'}/q_4$, and $L_4^{D,D'} = Q_4^{D,D'}/q_4$.

Maximum distance for local, distribution, primary, and express ways is $L_1^m = \max(L_1^{A,A'}, L_1^{B,B'})$, $L_2^m = \max(L_2^{B,B'}, L_2^{C,C'}, L_2^{D,D'})$, $L_3^m = \max(L_3^{C,C'}, L_3^{D,D'})$, and $L_4^m = L_4^{D,D'}$, respectively.

For simplicity, suppose that minimum travel distance of road with grade i is maximum travel distance of road with grade $i - 1$. Therefore, the minimum travel distance of local way, distribution way, primary way, and express way is $L_1^n = 0$, $L_2^n = L_1^m$, $L_3^n = L_2^m$, and $L_4^n = L_3^m$.

5.2. Travel Distance Distribution. Supposing that the average travel distance of local way is r_1, distribution way is r_2, and primary way is r_3; then [8]

$$r_1 = \frac{\int_0^{L_1^m} p(r)\, r\, dr}{\int_0^{L_1^m} p(r)\, dr}, \qquad r_2 = \frac{\int_{L_2^n}^{L_2^m} p(r)\, r\, dr}{\int_{L_2^n}^{L_2^m} p(r)\, dr},$$
$$r_3 = \frac{\int_{L_3^n}^{L_3^m} p(r)\, r\, dr}{\int_{L_3^n}^{L_3^m} p(r)\, dr}, \tag{8}$$

in which $p(r)$ is share ratio model of vehicles. According to [17], proportion function of vehicle travel is $P(r) = c(\exp(0.1r) - 1)$. r is travel distance, and c is parameter.

6. Example

(1) According to the principle, assume road space of local way, distribution way, primary way, and express way is $d_1 = 0.5$ km, $d_2 = 1.5$ km, $d_3 = 2.5$ km, and $d_4 = 5$ km, respectively. The origin network and traffic assignment network can be constructed.

(2) Calculate travel distance of each grade road. Suppose that OD volumes are all the same; that is, $q_1 = q_2 = q_3 = q_4 = 1000$ pcu/h. Traffic turnover and distance for each grade road are shown in Table 2.

Table 2: Traffic turnover (pcu·km) and travel distance (km).

Range	Local way		Distribution way		Primary way		Express way	
	Turnover Q_1	Distance L_1	Turnover Q_2	Distance L_2	Turnover Q_3	Distance L_3	Turnover Q_4	Distance L_4
A–A'	1500	1.5						
B–B'	452	0.452	2548	2.548	/	/	/	/
C–C'	/	/	2946	2.946	4054	4.054	/	/
D–D'	/	/	1427	1.427	2610	2.61	5963	5.963
Max. distance	1.5		2.9		4.1		6.0	
Min. distance	0		1.5		2.9		4.1	

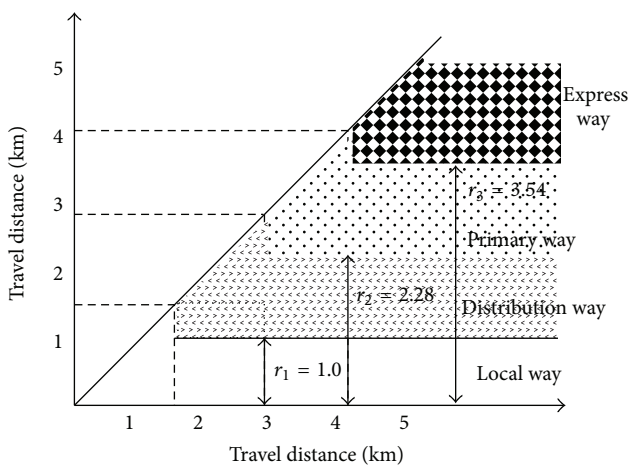

Figure 2: Travel distance distribution.

(3) Travel distance distribution:

distance of local way is $r_1 = \int_0^{1.5} c(e^{0.1r} - 1)r\,dr / \int_0^{1.5} c(e^{0.1r} - 1)dr = 1.0$, distance of distribution way is $r_2 = \int_{1.5}^{2.9} c(e^{0.1r} - 1)r\,dr / \int_{1.5}^{2.9} c(e^{0.1r} - 1)dr = 2.28$, and distance of local way is $r_3 = \int_{2.9}^{4.1} c(e^{0.1r} - 1)r\,dr / \int_{2.9}^{4.1} c(e^{0.1r} - 1)dr = 3.54$.

Travel distance distribution is shown in Figure 2.

7. Conclusions

In this paper, influence of traffic accidents on travel time reliability was considered, and a modified reliability model was proposed. According to vehicle characteristic, the maximum preponderant travel rang was defined, and four traffic assignment networks for each grade road were constructed. On the basis of new reliability model, regulation of route choosing was defined. Through traffic assignment, the maximum and minimum travel distance of each grade road were calculated. At last, an example was applied to confirm the feasibility of the model. However, only grid network was discussed, and other patterns should be considered further.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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