*Proc. of the 6th Intl. Symposium on Reliability Engineering and Risk Management (6ISRERM)*
*31 May – 1 June 2018, Singapore*
*Editor(s)* Xudong Qian, Sze Dai Pang, Ghim Ping Raymond Ong, Kok-Kwang Phoon


# FUNCTIONAL RELIABILITY OF URBAN ARTERIALS

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Quantitatively assessing how well an urban arterial road performs its function in operation, as opposed to the planning and design, is increasingly being demanded against problems such as unfulfillment of function. The urban arterial road system consists of urban expressways, major arterials and minor arterials, which mainly provide mobility or traffic function. First, typical characteristics of functional hierarchy for the urban arterial road system are demonstrated. Then this paper proposes the functional reliability approach based on the probabilistic method, aiming to evaluate the traffic function achievement degree of each type of urban arterial road. Finally, several urban arterials in Zhengzhou city are used for empirical studies. It is also verified that functional reliability is more effective to reflect the functional performance than level of service.

*Keywords*: urban arterials, traffic indices, functional reliability.

## 1 Introduction

Many countries have issued related technique standards to make the implementation of functional classifications mandatory. The latest one in China is the "Code for design of urban road engineering" (CJJ 37-2012, 2012). Urban roads are classified into four types, i.e., urban expressways, major arterials, minor arterials and local roads. It should be noted that functions allocated to minor arterials are the same as that of collectors in FHWA Functional Classification Guidance Update (2012) and Toronto road classification system (2013). Urban expressways, major arterials and minor arterials constitute the urban arterial road system (MHURD, 2010).

Functional classification is used throughout the project development process, influencing urban road network planning and design stages. However, at the operation stage, functional classifications are not involved. Performance of urban roads are usually evaluated in terms of level of service (LOS), which is based on average travel speed (Transportation Research Board, 2016). Besides, many factors such as population growth and economic expansion influences the use of road, raising the need to re-assess road functions (Guo and Xu, 2017). It is of significance to develop an appropriate method to evaluate functions of urban roads in the operation stage. Objectives of this paper are to propose a functional reliability method to assess the functional performance for the urban arterial road system, based on the probabilistic method.

## 2 Functional characteristics and traffic indices

In this study, we focus on traffic functions or mobility functions of the urban arterial road system. According to functional classifications in the "Code for design of urban road engineering" (CJJ 37-2012, 2012) in China, distinctions between traffic functions of urban arterial roads and corresponding indicators are identified in Table 1. An urban arterial's performance is described by using one or more quantitative measures that characterize some aspects of its traffic functions provided to the urban arterial road system.

**Table 1.** Intended roles and traffic indicators of urban arterial roads

| Road type | Key mobility function | Analysis elements | Traffic indicators |
|---|---|---|---|
| Urban expressway | Fast and continuous traffic | Basic expressway segment | Vehicle speed ( $v$ ); Coefficient of variation of headway ( $cv$ ). |
| Major arterial | Through traffic | Major arterial facility | Travel speed ( $v'$ ); Through-movement percentage ($S$); Traffic volume ($Q$). |
| Minor arterial | Collecting and distributing traffic | Minor arterial facility | Left-turn delay ( $t$ ). |

An urban expressway is usually a grade-separated urban arterial road with full control of access dedicated to the exclusive use of motorized vehicles. It prioritizes mobility, with an emphasis on undertaking high-speed, uninterrupted traffic flow. Hence, urban expressway segments are representative elements. Continuity indicates the quality of being continuous in space or time. Coefficient of headway variation here is used to reflect the fluctuating degree of continuous traffic flow.

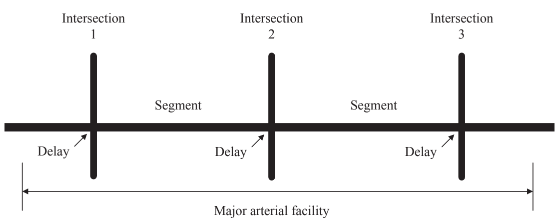



Figure 1. Urban major arterial facility.

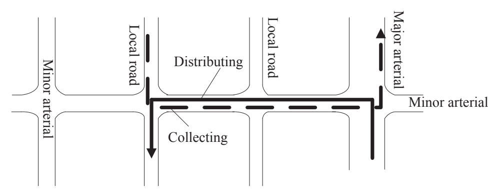



Figure 2. Minor arterial facility.

Traffic functions of major arterials are reflected in three aspects: carrying a large traffic volume, with a high travel speed and serving through traffic. The major arterial facility is selected as the element for function assessment (Figure 1). Travel speed of through vehicles is used to indicate influences of at-grade intersections. Delays at intersections are included in the travel time for calculating the travel speed. The through-movement percentage is used to characterize the function of serving through traffic. It is the ratio of vehicles go straight through several intersections continuously without turning on the major arterial facility to the total traffic volume on the facility.

Main functions of minor arterials (i.e., collectors) are to move traffic from local roads to arterials, and from arterials to the local roads. Turning behaviors at the intersection are necessary for accomplishing the collecting or distributing procedure. Compared to right-turning, left-turning leads to more traffic conflicts and is more complex. The left-turning delay is therefore selected to indicate the collecting or distributing efficiency. According to the spacing of urban roads, at least two local roads are laid between the minor arterial and the major arterial (Wang et al., 2017). Minor arterial facility is a set of intersections and segments for fulfilling the collecting and distributing function (see Figure 2).

## 3 Functional reliability methodology

The functional reliability (*FR*) of an arterial facility is the probability that it can perform its intended or designed function, for a specified interval, under stated conditions, without failure. It is a quantitative and probabilistic evaluation index of road function achievement degree, quantifying to what extent the road achieves the designed functions. This measure decomposes an arterial road into a set of traffic functions and expected behaviors under specified interval and stated conditions. This can be presented as follows:

$$FR = \Pr\{Traffic\ indices\ of\ functions\ are\ within\ acceptable\ levels\} \tag{1}$$

### 3.1 *Urban Expressway*

The calculation method of expressway functional reliability could be described in Eq. (2). It is the probability that the speed is above a certain threshold, and the headway variation coefficient is under a threshold simultaneously, within specific conditions and time. The formula is illustrated as follows:

$$FR^E = \Pr\left(v \ge v_0,\ cv \le cv_0\right) \tag{2}$$

where $v_0$ is the vehicle speed threshold; $cv_0$ is the threshold of headway variation coefficient.

Assuming that vehicle speed and headway variation coefficient are independent, the expressway functional reliability could be expressed as the product of probabilities that speed is above a certain threshold and headway variation coefficient is under a threshold within specified conditions and time:

$$FR^E = \Pr\left(v \ge v_0\right) \cdot \Pr\left(cv \le cv_0\right) \tag{3}$$

### 3.2 *Major Arterial*

The functional reliability for a major arterial facility is the probability that the travel speed is above a certain threshold, the traffic volume is above a threshold and the through-movement percentages is above a threshold simultaneously, within specific conditions and time. The formula is given as:

$$FR^M = \Pr\{Q \ge Q_0,\ v' \ge v_0',\ S \ge S_0\} \tag{4}$$

where $v_0'$ is the travel speed threshold; $S_0$ is the percentage threshold; $Q_0$ is the traffic volume threshold. Considering that traffic volume and vehicle speed are correlated, and the assumption that $v'$ and $S$ is independent, functional reliability of the major arterial could be derived:

$$FR^M = \Pr\{v' \le v_{0u}'\} \cdot \Pr\{S \ge S_0\} \quad (Under\ uncongested\ condition) \tag{5}$$

$$FR^M = \Pr\{v' \ge v_{0l}'\} \cdot \Pr\{S \ge S_0\} \quad (Under\ congested\ condition) \tag{6}$$

where $v_{0u}'$ and $v_{0l}'$ are the upper and lower threshold for $v'$, respectively. Volume to capacity ratio (V/C) can be used as a reference for the speed threshold.

### 3.3 *Minor Arterial*

The functional reliability of a minor arterial facility can be described as the probability that vehicles realize the left-turning behaviors at two intersections, within the specified conditions and time, at the acceptable delay level. It is computed as:

$$FR_i^C = \Pr(t_{ij} \le D_{ij}),\ i = 1,\ 2,\ j = 1,\ 2 \tag{7}$$

where $i=1$ denotes collecting; $i=2$ denotes distributing; $j=1$ is the intersection of minor arterial and local road; $j=2$ is the intersection of major arterial and minor arterial; $t_{ij}$ is the delay of a vehicle; $D_{ij}$ is the delay threshold. The collecting and distributing functional reliability can be further written as follows:

$$FR_1^C = \Pr(t_{11} \leq D_{11},\ t_{12} \leq D_{12}) \tag{8}$$

$$FR_2^C = \Pr(t_{21} \leq D_{21},\ t_{22} \leq D_{22}) \tag{9}$$

If the left-turning behaviors at two intersections are independent, Eq. (8) will be:

$$FR_1^C = \Pr(t_{11} \leq D_{11}) \cdot \Pr(t_{12} \leq D_{12}) \tag{11}$$

$$FR_2^C = \Pr(t_{21} \leq D_{21}) \cdot \Pr(t_{22} \leq D_{22}) \tag{12}$$

## 4 Case studies of urban arterial roads in Zhengzhou city

### 4.1 *Urban expressway*

Field surveys were conducted at two urban expressway segments of Western 3rd Ring and Jingsha Expressway. SONY HDR-CX290 video camera was set up in the field to record traffic data. The data were collected during 7:30-8:30 AM. The average value of vehicle speeds in 2 mins and the headway variation coefficient of headways in 2 mins are utilized for correlation analysis. The StatTools of Palisade is used to fit the relationship of vehicle speed and headway variation coefficient. 28 nonlinear functions, including logarithmic, inverse, and quadratic etc are covered (Palisade Corporation, 2015). The maximum goodness of fit ($R^2$) is 0.266. Overall, vehicle speed can be regarded as being independent of the headway variation coefficient.

Indices for service level analysis of two investigation segments are shown in Table 2. The designed service level of urban expressways is Level 3 (CJJ 37-2012, 2012). Performance of Jingsha expressway agrees well with the designed service level. Thresholds of $v_0$=36 km/h and $cv_0$=0.7 are used (GB/T 33171-2016). Functional reliability values for expressway segments are also shown in Table 2. Calculating results of Eqs. (2) and (3) are consistent. Jingsha Expressway has higher functional reliability, suggesting that the realizing extent of its function is better. Western 3rd Circle Expressway has higher service level. However, its functional reliability is low, because it does not play its role of continuous traffic due to the low traffic density.

**Table 2.** Service levels of urban expressway segments

| Sites | Density [pcu/(km·ln)] | Average vehicle speed (km/h) | LOS | Functional reliability | |
|---|---|---|---|---|---|
| | | | | Eq. (2) | Eq. (3) |
| Jingsha Expressway | 28.99 | 43.57 | Level 3 | 0.65512 | 0.63333 |
| Western 3rd Ring | 12.71 | 67.17 | Level 2 | 0.49915 | 0.50000 |

### 4.2 *Major arterial*

Two major arterial segments sites on Kexue Road and Dongfeng Road are used for field data. The investigation time period was from 7:30 to 11:30 AM. 96 sets of 5-min traffic data were collected. Also, the StatTools of Palisade is used to fit the relationship of travel speed and through vehicle percentage. The maximum goodness of fit is 0.101 and the minimum value is 0.000. Overall, travel speed is considered as being independent of through vehicle percentage.

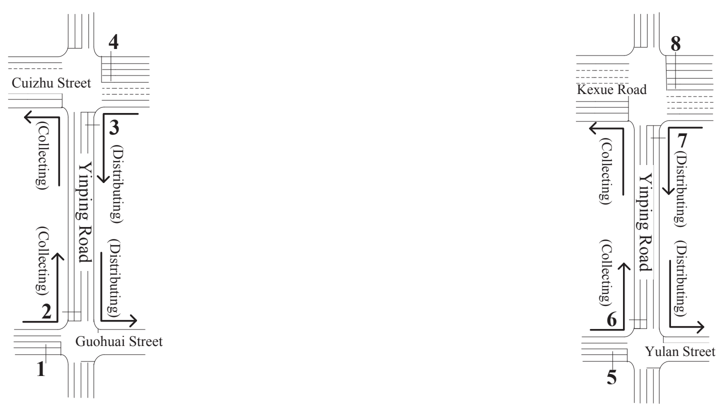
Service levels for two major arterial segments are determined based on the average travel speed according to HCM (Transportation Research Board, 2016). As shown in Table 3, the level of service for Dongfeng Road is C. Under the uncongested time period, the level of service for Kexue Road is D; while under the congested time period, the service level is D.

**Table 3.** Service levels for Kexue Road and Dongfeng Road facilities

| Facility | Kexue Road | | Dongfeng Road |
|---|---|---|---|
| | Peak hours (7:30-9:30 AM) | Non-peak hours (9:30-11:30 AM) | |
| Average travel speed (km/h) | 31.6 | 46.3 | 24.0 |
| Level of service | D | C | C |
| Functional reliability | 0.803 | 0.702 | 0.386 |

According to speed-flow relationships, for Kexue Road, there is an obvious bound for speed-flow relationships under uncongested and congested conditions; while for Dongfeng Road, traffic data fall in the congested conditions. Assuming travel speed thresholds are determined based on V/C=0.6, corresponding upper and lower thresholds for Kexue Road are 55 km/h and 24 km/h, respectively; the lower threshold for Dongfeng Road is 20 km/h. The average through-movement percentage of Kexue Road is 0.803; while Dongfeng Road is only 0.421. It is difficult to choose a uniform threshold for the through-movement percentage under this situation. The average value is used as the threshold. Functional reliability values for two major arterial facilities are demonstrated in Table 3. Compared with LOS, functional reliability results show different performance. Under peak hours, though the average travel speed of Kexue Road is low, the probability that the travel speed falls within the expected threshold range is higher; while for Dongfeng Road, the poor performance of through-movement leads to low functional reliability.

### 4.3 *Minor arterial*




(a) Yinping Road facility -1 (b) Yinping Road facility -2

Figure 3. Survey sites of two minor arterial facilities.

Two minor arterial facilities are used for field data collection units, shown in Figure 3. Yinping Road is the minor arterial. Guohuai Street and Yulan Street are local roads. Cuizhu Street and Kexue Road are major arterials. Detection points (1-8) are selected at stop lines of approaches at four signalized intersections. The survey time is 17:00-18:00 PM. Delay and turning behaviors of each vehicle are obtained. Delays of 100 vehicles at adjacent intersections are recorded and analyzed by SPSS statistical software. The maximum Pearson correlation value is -0.082. Nonlinear correlation tests are conducted using the 28 nonlinear functions in Palisade. The maximum goodness of fit ($R^2$) is only 0.042. The left-turning delays at adjacent intersections are irrelevant, and moreover independent. Using 60s as the acceptable delay threshold, the functional reliability of Yinping Road facility-1 and Yinping Road facilities-2 are shown in Table 4. The collecting and distributing functional reliability of Yinping Road facility -1 is 0.809 and 0.805, respectively, which are both higher than that of Yinping Road facility -2.

Take the intersection of Yinping Road and Kexue Road as an example. The average delay of all vehicles is 18s/veh and its LOS is Level 1 (CJJ 37-2012). However, its average left-turn delay is 66.5 s. Because the average delay of all vehicles at the intersection related to LOS is an aggregate indicator, it is inconsistent with the left-turn performance that interprets collecting and distributing functions. Obviously, functional reliability reflects the practical operation better.

**Table 4.** Function reliability values and average delay of left-turn

| Facility | Procedure | Functional reliability |
|---|---|---|
| Yinping Road facility -1 | Collecting | 0.809 |
| | Distributing | 0.805 |
| Yinping Road facility -2 | Collecting | 0.143 |
| | Distributing | 0.059 |

## 5 Conclusions

Quantitative assessment on the functional classification performance of the urban arterial road system is essential for road planning, design and operation. This paper proposes the functional reliability method for assessing the urban arterial road facilities. Calculating findings and comparison with level of service analysis results illustrate the feasibility of the proposed methodology. Future work will focus on threshold values. System reliability of the urban arterial road network could be evaluated based on the element reliability, which is also a future topic.

## Acknowledgements

This work was supported by the National Natural Science Foundation of China [Grant Number 51278468].

## References

CJJ 37-2012, *Code for Design of Urban Road Engineering*, 2012.

Federal Highway Administration (FHWA), *Highway Functional Classification Concepts, Criteria, and Procedures*, 2013.

GB/T 33171-2016, *Specification for Urban Traffic Performance Evaluation*, 2016.

Guo, M. and Xu, Y. C., *Traffic Facilities | Road Classification System in China Should Meet Needs of the Times*, www.sohu.com/a/149105908_260616?_f=index, recom, 2017.

Ministry of Housing and Urban-Rural Development of the People's Republic of China (MHURD), *Guidelines for Urban Comprehensive Transport System Planning*, 2010.

Palisade Corporation, *Statistics Add-in for Microsoft Excel (version 7)*, www.palisade.com/downloads/documentation/75/CN/StatTools7_CN.pdf, 2015.

Toronto Transportation Services, *City of Toronto Road Classification System*, 2013.

Transportation Research Board, *Highway Capacity Manual*, 2016.

Wang, D. W., Li, H., Li, Y. and Yan, Y. D., *Analysis of Road Section Correlation and Road Distance in Urban Road Network*, Journal of Traffic and Transportation Engineering, 17(1): 101-108, 2017.