Access for Performance of Transportation Planning and Operations: Case Study in Beijing Metropolitan Region

Y. G. Wang*[1], C. B. Zhang[2], Y. Cao[3], B. H. Liu[4]

[1,2] School of Highway, Chang'an University, Xi'an 710064, China
*sdqdwyg@163.com
[3] Traffic & Transportation School, Dalian Jiaotong University, Dalian 116028, China
[4] Transportation institute, Shijiazhuang Tiedao University, Shijiazhuang 050043, China

ABSTRACT
Considering the importance of maintaining effective performance at desired levels, the *Transportation Adaptability Performance Index*, as a weighted multi-criteria combination approach, is proposed to continuously identifying the performance of degradable transportation networks and making effective supplement, contrapuntal revision and in-time adjustment of the program implementation process, in response to new requirements of the urban system. For the design of strategic and quantitative methodology, 50 variables belonging to 8 domains in 2 components are chosen as the original input inherently reflecting the various interests of involved stakeholders. Specifically, the paired comparison matrix of the domain is constructed by the analytic hierarchy process to weight the importance of each single variable. If the consistency of the matrix is acceptable, the domain weight in two components is determined directly through the singular value decomposition approach and while the consistency level is unacceptable, the significant element in the matrix is identified and revised until the consistency satisfies the constraint. The methodology is then applied to evaluate the performance of transportation networks in Beijing metropolitan region using the derived 2000~2010 data and the findings indicate that the hidden and potential problems could be quantitatively identified by this approach that can be used as a user-friendly tool for metropolitan planning organizations in assessing the effectiveness and efficiency of in-service infrastructures, updating plans, setting priorities and optimizing resource allocation for next step.

Keywords: transportation planning, adaptability performance index, paired comparison matrix, acceptable consistency, singular value decomposition, significant element.

Abbreviation Terms

AADT	Annual average daily traffic
API	Air pollution index
ASD	Average stopped delay
BRT	Bus rapid transit
CI	Consistency index
CR	Consistency ratio
GDP	Gross domestic product
HCM	Highway capacity manual
ITS	Intelligent transportation system
LOS	Level of service
km	Kilometer
NAAQS	National ambient air quality standards
RI	Random index
SVD	Singular value decomposition
TIA	Traffic impact analysis
veh	Vehicle

1. Introduction

To evaluate the effectiveness of transportation planning in urban regions, the interaction between all the activities in the urban regions and their relevant impact in the urban economy, the society and the ecological environment must be taken into consideration together since the primary purpose of transportation planning is to construct a viable and efficient support for urban economy development, maintain the equity and social inclusion and reduce the environmentally negative impacts [1]. Concerning this statement, it is very important to evaluate the transportation network performance in order to diagnose the existing problems in the implementation process and adequate it to a real sustainable urban development.

Performance variables, also known as performance objectives, targets, measures, or measures of effectiveness (MOEs), are indicators that evaluate the progress toward “success” in achieving the original stated goals or aims. Though it is not specific to transportation, much has been reported regarding the use of performance variables to monitor and improve the effectiveness of the implementing transportation programs and more than 500 detailed variables have been developed [2, 3]. Such performance variables may track one specific goal: with a focus on congestion, a series of congestion related variables may be unarguably able to monitor the system’s operation and efficiency [4]. However, the growing recognition of the inevitability of traffic congestion gauges progress towards a new philosophy of transportation planning strategies [5, 6], which include not only expansion of existing facilities, but better operation harmony in an overall system of environment, society and economy dependently.

Unlike the capacity-oriented concept, sustainable transportation planning is about a multimodal transportation network providing mobility and safety to its users, and considers transportation planning as a part of the urban system and is concerned with the goals of safety, livable communities, economic, energy, land use and air quality [4, 7]. Most recently, therefore, how to measure and assess the effectiveness of implementing transportation planning in supporting urban system has attracted various research interests [8, 9], especially in developing countries like China [10], so as to provide a direct understanding for the different involved stakeholders (planners, builders, managers and users) as well as to contribute a shift in re-considering the draft programs and implementation plans [11]. Nowadays, long-range transportation planning (LRTP) is too little and LRTPs mostly have evolved from their initial long-range plans into short-term programs by enriching and updating the early agreements at different implementation stages in a project’s budget, design, and schedule [12]. For example, an updated LRTP (Six Year Improvement Programs, SYIP), in Hampton Roads region of Virginia, is actually used rather than seeing consistent in 25-year period [2].

Unfortunately, however, similar issues have not been considered as a part of the overall transportation planning process for decades in Chinese cities. Despite having released its first LRTP in the beginning of 1980s, Beijing has drafted a new LRTP that lasted until 2004, and during these periods, few new demands were considered and supplemented to certain contents [13]. Therefore, as expected, it is necessary to develop a monitoring and evaluating procedure based on transportation variables related to urban system dimensions in China [14, 15]. Hence, this paper presents research contributing to optimize some performance variables that characterize transportation adaptability for China’s specific condition in the metropolitan area and formulate an indicator based multi-criteria modeling process.

2. Data

Obviously, transportation planning is independent from environment, society and economy, and thus an effective and adaptable project should support the effective development of the urban system [16, 17], which features five objectives accordingly: 1) human-oriented facilities and livable streets; 2) friendly accessibility, health and safety; 3) equity and social inclusion; 4) support of a viable and efficient economy; 5) protection of the natural and ecological environment.

For simplification, the performance variables here are categorized into two components (Component A and B) belonging to 8 domains, namely: a) social development, b) economic growth, c) life quality, d) ecological environment, e) reliability, f) efficiency, g) safety, h) operation. The first four domains in Component A are summarized as they highlight the systemic urban development progress while being more or less, directly or indirectly, influenced by the level of transportation network performance. The last four domains in Component B are of most significance in extensively monitoring and reporting the transportation network performance in detail.

To illustrate the applicability of the multi-criteria variable approach in measuring the performance of transportation networks, this study has used the Beijing metropolitan region as a case study. During the recent two decades, the population of Beijing city and vehicle ownership have grown rapidly, which has brought increasing challenges to the transportation networks [13]. In response to the increasing traffic demand, the transportation authorities have invested to develop an effective transit-oriented urban transport system to tickle the traffic congestion problems [13, 14, 17]. Here, 50 single variables are originally developed, as shown in Tables 1 and 2, respectively, for estimating the performance of regional transportation plans and operations, as a case example, and Table 3 summarizes the original 50 hierarchical variables over 2000-2010 statistics from governmental reports.

Performance variable	Unit	Definition items	Type	Sym
Social development				O_1
Urbanization level	%	A national economic and social development of integrated objectives, including population, land resources, et al	I	x_1
Population density	p/km^2	Population per unit area or unit volume	II	x_2
Gini coefficient		Inequality of income or wealth distribution	II	x_3
Unemployment	%	Unemployment proportion	II	x_4
Health service level	Sheet	Hospital beds per 100,000 persons	I	x_5
Education investment rate	%	% financial expenditure in education	I	x_6
Driver education	%	% drivers in education and training	I	x_7
Economic growth				O_2
GDP per capita	10000 CNY	GDP / registered citizen population	I	x_8
Social service	%	Tertiary industry / GDP	I	x_9
Industrial efficiency index	%	Measure of industrial enterprises' economic efficiency	I	x_{10}
Retail sales per capita	CNY	Retail sales / registered citizen population	I	x_{11}
Life quality				O_3
Engel coefficient	%	% expense on food	II	x_{12}
Living comfort	m^2	Living space per capita	I	x_{13}
Motorization	pcu	Vehicle ownership per 10,000 people	I	x_{14}
Travel expenditure	%	% annual expenditures on travel	II	x_{15}
Clean energy consumption	%	% clean energy consumption for ultra-low emission	I	x_{16}
Ecological environment				O_4
Environmental utilization	m^2	Green space per capita	I	x_{17}
Environment protection	%	% investment in environmental protection	I	x_{18}
Weather quality index	%	% days above level 2 in a year	I	x_{19}
API		A composite index measuring air pollution	II	x_{20}
Noise pollution	dB	Average regional environmental noise	II	x_{21}
% intersections heavily polluted	%	% intersections beyond NAAQS	II	x_{22}
% segments heavily polluted	%	% road segments beyond NAAQS	II	x_{23}
Dust pollution	10000-ton	Dust emissions per year	II	x_{24}
Environment protection	%	% areas sensitive to emission and noise under protection	I	x_{25}
Road greening	km/km^2	Km road greening level per unit area	I	x_{26}

Table 1. Explanatory performance variables of Component A.

Performance variable	Unit	Definition items	Type	Sym
Reliability				O_5
Road distribution	km/100 km^2	Road network density	I	x_{27}
Road equality for residents	m^2	Road areas per capita	I	x_{28}
Road equality for vehicles	m^2	Road areas per veh	I	x_{29}
Freight volume	10000-ton	Annual Freight Tonnage	I	x_{30}
Transit facilities	stb	Number of buses per 10,000 persons	I	x_{31}
Pedestrian accommodations	%	% km with sidewalk coverage	I	x_{32}
Bicycle users	%	% km with bike lane / shoulder coverage	I	x_{33}
Efficiency				O_6
% transit	%	Travel proportion in transit	I	x_{34}
90 % Trip time	%	Maximum trip time accepted by 90% travelers	I	x_{35}
Vehicles per lane km		AADT × length / lane km	II	x_{36}
Transit service	min	Average bus wait time	I	x_{37}
Hub service	%	% individual perception of hub LOS	I	x_{38}
ITS	%	% km coordination with capable variable message signs	I	x_{39}
Operation				O_7
% segment heavily congested	%	% km at LOS E or F	II	x_{40}
% intersections heavily congested	%	% intersections at LOS E or F	II	x_{41}
Delay savings	s/km	Average travel delay per km	II	x_{42}
Transit support	%	% intersections with buses signal priority	I	x_{43}
Policy & regulation	%	% programs that undertook TIA	I	x_{44}
Opportunities provision	10000	Jobs offered in planning process	I	x_{45}
Safety				O_8
Traffic accident risk	mvk	Accidents per million veh-km	II	x_{46}
Seriousness of accident		Fatalities / injuries	II	x_{47}
Safety management	%	% arterial intersections intelligently controlled	I	x_{48}
Safety equipments	sheet/km	Signs per km per lane	I	x_{49}
Pedestrian safety	%	% individual awareness above safety	I	x_{50}

Table 2. Explanatory performance variables of Component B.

Among these variables, LOS is a general measure of traffic operating conditions within an intersection or roadway section. HCM 2000 defines six levels of service and each level has a definition indicated by a letter, from A to F, with LOS A representing the best operating conditions and LOS F the worst. For intersections, LOS is determined by the ASD per vehicle and LOS E describes very congested driving conditions with delays averaging greater than 55 and up to 80 seconds per vehicle for signalized intersection and 35<ASD<50 for unsignalized intersection, respectively. Signalized or unsignalized intersection that has LOS F means the ASD greater than 80 or 50 seconds per vehicles. For urban streets, the roadway under LOS E has significant delays with average travel speeds of one-third or less of the free flow speed (greater than 35mph). Moreover, traffic condition becomes much worse when the LOS reduces from E to F and the travel speed is extremely low, typically 33 or 25% of the free flow speed.

However, the original input variables do not have a uniform format and it is difficult to compare the variables in each domain. On setting the maximal, minimal of optimal thresholds interactively through the characteristics of each variable and the user's references, we standardize any variable x_{ij} in domain *i*.

For the-bigger-the better variable (type I):

$$\mu_{ij} = \frac{x_{ij} - x_{ij,\min}}{x_{ij,\max} - x_{ij,\min}} \quad (1)$$

For the-smaller-the- better variable (type II):

$$\mu_{ij} = \frac{x_{ij,\max} - x_{ij}}{x_{ij,\max} - x_{ij,\min}}. \quad (2)$$

3. Methodology

3.1 Single variable integration

In each domain, there are no less than two single variables and each variable has a different contribution or influence on the total performance of domain. Here we assume that the importance of an individual variable is specified as a proportion of deviation of the given-domain variable to the cumulative deviations of all variables. For domain *i* with *m* variables, the deviations of variable *j* over *n* years can be given as $\sum_{l=1}^{n} \left| \mu_{ij}(t) - \mu_{ij}(l) \right| w_j$, and, therefore, the solution of the weight vector for domain *i* refers to the optimization access [18]:

$$\begin{cases} \max \sum_{j=1}^{m} \sum_{l=1}^{n} \left| \mu_{ij}(t) - \mu_{ij}(l) \right| w_j \\ \text{s.t.} \quad w_j \geq 0, j \in m, \sum_{j=1}^{m} w_j^2 = 1 \end{cases} \quad (3)$$

And, thus, it reaches the weight expression as:

Sym	Variable statistics											Max	Min	Weigh
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010			
x_1	31.5	32.3	34.6	36.0	36.8	38.7	40.1	42.3	44.7	47.3	50.8	75	20	0.042
x_2	4871.5	4953	5031	5101	5168	5269	5317	5435	5549	5734	5913	7500	800	0.270
x_3	0.265	0.273	0.287	0.294	0.307	0.325	0.369	0.383	0.397	0.411	0.419	0.5	0.15	0.130
x_4	4.7	5.2	4.3	3.8	4.3	3.9	3.5	3.7	3.8	4.0	3.9	7	0	0.081
x_5	14.36	14.79	15.24	14.86	14.71	14.62	14.58	14.76	14.82	14.91	15.06	40	5	0.006
x_6	3.68	3.43	3.21	2.60	2.25	1.69	1.43	1.75	1.92	2.14	2.33	4	1	0.338
x_7	67	73	75	68	62	64	67	73	70	66	63	100	20	0.133
x_8	2.41	2.70	3.08	3.49	4.11	4.54	4.73	5.02	5.09	5.16	5.34	8	1.5	0.161
x_9	32.5	32.9	34.7	35.6	36.4	36.9	38.1	39.3	41.7	43.9	45.5	60	20	0.142
x_{10}	103.65	109.73	118.41	122.61	135.17	142.85	137.68	134.79	131.75	128.47	131.64	150	100	0.379
x_{11}	2128	2407	2876	3208	3519	3503	3729	4133	4371	4408	4576	6000	1000	0.318
x_{12}	40.6	39.2	38.4	37.1	35.3	34.4	34.1	32.0	31.1	29.1	28.4	50	15	0.083
x_{13}	9.3	14.1	16.0	18.7	21.3	19.7	22.9	24.3	25.7	26.2	27.3	40	5	0.131
x_{14}	1306	1466	1627	1807	1929	2161	2245	2287	2317	2393	2468	4500	1000	0.047
x_{15}	2.71	3.00	6.65	8.31	6.63	8.31	10.12	9.36	9.94	10.36	11.44	15	0	0.422
x_{16}	4.8	5.2	6.8	8.9	11.3	12.5	13.1	13.6	14.0	14.7	15.3	20	0	0.317
x_{17}	8.68	8.92	9.35	9.60	10.03	11.11	11.79	12.34	12.96	13.47	14.12	15	3	0.147
x_{18}	4.7	4.3	4.3	4.0	3.3	2.6	2.4	2.1	2.0	2.3	2.1	6	0	0.120
x_{19}	43.9	56.8	62.7	74.9	80.6	90.9	96.8	98.4	98.9	99.2	99.8	100	0	0.243
x_{20}	4.72	3.61	3.74	3.33	3.29	3.29	3.13	2.98	2.81	2.73	2.69	5	0	0.023
x_{21}	63.5	61.7	56.7	52.8	49.1	48.2	49.3	44.5	42.7	43.1	40.4	75	30	0.092
x_{22}	18	15	12	9	11	10	12	11	11	10	10	25	5	0.098
x_{23}	78.1	72.4	65.2	57.4	53.8	45.6	42.4	38.7	37.5	35.8	34.1	85	25	0.116
x_{24}	10.03	9.03	8.09	7.08	7.01	5.76	5.25	5.01	4.86	4.72	4.69	15	0	0.085
x_{25}	21.5	22.7	22.9	23.7	25.8	28.6	33.4	36.7	38.2	39.7	41.3	100	0	0.024
x_{26}	66.82	74.39	74.02	73.08	70.24	69.62	64.13	63.32	66.3	70.4	72.1	100	30	0.052

Table 3. Data acquisition and performance variables for Component A.

Source: the reference variables are directly collected from 'Beijing Statistical Yearbook (2001~2010)', "Beijing Environment Situation Bulletin (2000~2010)", "Report of Beijing Traffic Noise Situation Survey (2006, 2010)", etc.

Sym	Variable statistics											Max	Min	Weigh
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010			
x_{27}	80.68	81.76	85.43	82.98	87.0	90.68	91.37	91.84	92.04	93.42	94.15	120	70	0.154
x_{28}	6.29	7.49	7.82	10.51	10.30	10.32	10.46	10.55	11.07	11.66	12.32	30	5	0.044
x_{29}	29.02	30.90	29.16	35.38	32.48	29.18	28.87	28.46	28.14	27.63	26.28	45	10	0.322
x_{30}	2.80	2.83	2.84	2.84	2.93	3.01	3.12	3.29	3.33	3.51	3.59	5	1	0.103
x_{31}	7.3	7.5	8.9	9.5	11.7	13.6	15.4	19.1	20.7	21.2	23.4	35	5	0.110
x_{32}	45.1	49.3	46.7	53.8	59.7	55.6	63.9	65.0	66.3	67.9	69.0	100	30	0.191
x_{33}	5.3	5.5	6.4	7.1	7.8	8.5	9.6	9.8	10.2	10.8	11.6	20	5	0.076
x_{34}	26.5	25.7	25.5	23.2	26.0	28.1	30.1	33.1	35.6	37.3	39.5	70	15	0.020
x_{35}	21.5	19.6	22.5	21.2	27.4	29.5	32.3	34.5	36.3	35.8	38.4	40	10	0.217
x_{36}	0.75	0.72	0.69	0.73	0.79	0.85	0.83	0.91	0.93	0.95	0.91	1.2	0.5	0.114
x_{37}	21.3	18.7	13.6	9.7	13.7	10.7	10.9	8.8	9.3	8.7	8.6	30	5	0.443
x_{38}	37	39	44	46	51	55	62	56	65	71	78	100	30	0.075
x_{39}	22.7	28.6	31.2	33.5	42.7	38.9	31.4	28.3	33.4	35.7	38.9	60	15	0.131
x_{40}	16.2	17.1	22.4	23.6	21.8	25.7	26.5	23.9	25.7	28.9	27.1	40	8	0.185
x_{41}	14	16	19	22	19	23	17	19	17	21	22	30	10	0.255
x_{42}	8.7	8.3	7.7	8.2	7.9	8.1	9.4	9.3	9.7	10.1	10.6	15	0	0.026
x_{43}	5	11	15	19	22	26	35	38	42	46	51	80	0	0.038
x_{44}	43	52	68	74	80	89	100	100	100	100	100	100	0	0.317
x_{45}	0.5	0.65	0.75	1.23	1.15	1.61	1.38	1.84	1.73	1.79	1.88	2	0.35	0.179
x_{46}	5.32	5.07	4.85	4.21	4.57	3.76	3.23	2.69	2.55	2.47	2.31	8	0	0.1757
x_{47}	0.21	0.25	0.33	0.36	0.31	0.27	0.29	0.24	0.21	0.19	0.18	0.5	0.1	0.6685
x_{48}	5.75	7.25	8.88	14.25	17.13	21.75	28.63	30.25	33.29	35.73	38.97	100	0	0.0432
x_{49}	5.3	5.5	6.4	7.1	7.8	8.5	9.6	9.8	10.1	11.7	13.2	20	5	0.0635
x_{50}	31.5	30.4	34.0	28.7	30.2	33.1	41.7	35.6	42.6	45.1	49.9	100	0	0.0491

Table 4. Data acquisition and performance variables for Component B.

Source: the reference variables are directly collected from ‘Beijing Statistical Yearbook (2000~2010)’, ‘Beijing Transport Development Annual Report (2000-2010)’, ‘Report of the Second Urban Comprehensive Traffic Survey in Beijing (2000), ‘Report of the Third Comprehensive Traffic Survey in Beijing (2007)’, ‘Report of the Forth Comprehensive Traffic Survey in Beijing (2010)’, etc.

$$\{w_{ij}\} = \frac{\sum_{l=1}^{n} \left| \mu_{ij}(t) - \mu_{ij}(l) \right|}{\sum_{j=1}^{m} \sum_{l=1}^{n} \left| \mu_{ij}(t) - \mu_{ij}(l) \right|} \qquad (4)$$

Finally, the performance of domain i is represented through the weighted linear integrations of all deviations of m variables. That is, mathematically:

$$P_i = \sum_{j=1}^{m} w_{ij} \mu_{ij} \qquad (5)$$

3.2 Domain Weight Estimation with Paired Comparison Matrix [19]

To form the paired comparison matrix for weighting the importance of each domain in two components, different stakeholders are interviewed in order to reflect their personal opinions and feelings on each domain, and each component pair (m, n) as a comparison judgment r_{mn} (m, n = 1, 2,…, 4) in response to the importance ratio of variables m and n is developed by assigning a number from

Satty's nine-point scale, where, 1 represented "equal importance", 3 denoted "moderate importance", 5 stood for "strong importance", 7 meant "very strong importance", and 9 was "extreme importance", representing the ratio of their importance contributing to their upper-level component [20].

Thus, each comparison value a_{ij} equals to w_i / w_j exactly, if the exact weights vector $w = \left(w_1, \ldots, w_n\right)^{\mathrm{T}}$ are known. In this case, a pairwise comparison matrix A can be written as:

$$A = \begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & & a_{2n} \\ \vdots & & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{pmatrix} = \begin{pmatrix} 1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & 1 & & w_2/w_n \\ \vdots & & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & 1 \end{pmatrix} \tag{6}$$

For an input matrix A∈$R^{m\times n}$, with rank r, r ≤ min(m, n), the SVD of A can be written in the form of [21]:

$$\mathrm{A} = \mathrm{UDV}^{\mathrm{T}} = \sum_{i=1}^{k} \sigma_i u_i v_i^T \tag{7}$$

where D = [$diag$ $(\sigma_1, \sigma_2, \cdots, \sigma_r)$, O] or its transposition determined by $m<n$ or $m>n$, while O is zero matrix and $0 < \sigma_k \le \cdots \le \sigma_2 \le \sigma_1 \in R$. These σ_i (i=1, 2, …, r) are denoted as the singular values of matrix A. U and V are two orthogonal matrices with U = [u_1, u_2, …, u_m]∈$R^{m\times m}$ and V = [v_1, v_2, …, v_n]∈$R^{n\times n}$. Here, u_i and v_i are termed the left and right singular vectors of A, respectively, in response to singular value i.

Let a pairwise comparison matrix A be given, where $a_{ij} = 1/a_{ji}$ and $a_{ij} = a_{ik}/a_{jk}$ for any i, j, and k, thus it is a positive matrix with reciprocality and consistency and its weight satisfies [22]:

$$W_i = \frac{u_i}{\sum_{j=1}^{n} u_j} = \frac{\frac{1}{v_i}}{\sum_{j=1}^{n} \frac{1}{v_j}} \tag{8}$$

But if a_{ij} is not always equal to a_{ik}/a_{jk} for all i, j, and k, the consistency of matrix A is acceptable, and the determination of the weight vector could be converted into [22]:

$$\begin{cases} \min\left[\mathrm{D}\left(u \,\|\, W\right) + \mathrm{D}(\frac{1}{v} \,\|\, W) \right] \\ s.t. \quad \sum_{i=1}^{n} W_i = 1 \end{cases} \tag{9}$$

That is, the weight vector is expanded into:

$$W_i = \frac{u_i + \frac{1}{v_i}}{\sum_{j=1}^{n} \left(u_j + \frac{1}{v_i} \right)} \tag{10}$$

3.3 Consistency Improvement of Paired Comparison Matrix [19]

For a paired comparison matrix A, its consistency should be checked through the CR value, according to Satty's formula [20]. If $CR > 0.1$, the matrix A is invalid in consistency and should be adjusted repeatedly until $CR \le 0.1$.

Generally, their distance between two real numbers x and y is defined as:

$$d(x, y) = \frac{|x - y|}{\max(x, y)} \tag{11}$$

For a pairwise comparison matrix with low level of inconsistency, the distance between each row vector e_i and the W vector corresponding to $\lambda_{\max}$ is given by [23]:

$$d_i = \frac{1}{n} \sum_{j=1}^{n} \frac{\left| e_i^j - W_j \right|}{\max(e_i^j, W_j)}\,, \tag{12}$$

and all row vectors fluctuate around W and the fluctuation amplitude also reflects its level of inconsistency. Obviously, the row vector with the longest distance to W has the most significant effect on the matrix consistency. Subsequently, the row L of significant element e_{LH} in inconsistency matrix *A* could be identified through d_L=max(d_i). Repeatedly, the distance d_{Li} between e_L and *W* could be given by Eq. (13) to identify the maximum d_{LH}=max(d_{Li}) and determine the column *H* of significant element e_{LH}.

$$d_{Li} = \frac{\left|e_L^i - W_i\right|}{\max(e_L^i, W_i)}. \qquad (13)$$

If the average $\overline{e}_{LH}$ equals to $\frac{1}{n}\sum_{j=1}^{n} e_{Lj}/e_{Hj}$, thus e_{LH} could be modified into:

$$e_{LH}^* = \frac{1}{2}\left(\overline{e}_{LH} + \frac{1}{\overline{e}_{LH}}\right). \qquad (14)$$

The element e_{HL} in matrix A is then replaced by $1/e_{LH}^*$ and the consistency of pair comparison matrix *A* is improved. Thus, the weigh vector could be determined by Eq. (8) or (10).

3.4 Performance Indicator Profile

Thereafter, the total contribution of specific variables and domains to the performance of a specific transportation planning project and operation could be measured by the single variables integrated from domains to components. Particularly, the performances of component A (urban system) and component B (transportation network) can be statistically re-weighted through the domain performances as:

$$I_{\text{urb, tra}} = \sum_i W_i^{\text{urb, tra}} P_i^{\text{urb, tra}} \qquad (15)$$

To measure the overall performance of transportation network quantitatively, an indicator, *Transportation Adaptability Performance Index* (*TAPI*), is formatted to monitor and keep track of the planning process in the interval and help understand precisely how the implementation process is going over time, on the assumption that the performance of transportation planning and operation could be quantified by the integration and combination of the single variable.

Here *TAPI* is specified as the ratio of performance differences (I_{urb} & I_{tra}) of the two components over *t*, and it yields a generalized ordered model as [19]:

$$\Delta_{\text{TAPI}} = \theta \cdot \sqrt{\left|\left(I_{\text{tra}}^t - I_{\text{tra}}^0\right) / \left(I_{\text{urb}}^t - I_{\text{urb}}^0\right)\right|} \qquad (16a)$$

$$\theta = \frac{\left(I_{\text{tra}}^t - I_{\text{tra}}^0\right)\cdot\left(I_{\text{urb}}^t - I_{\text{urb}}^0\right)}{\left|\left(I_{\text{tra}}^t - I_{\text{tra}}^0\right)\cdot\left(I_{\text{urb}}^t - I_{\text{urb}}^0\right)\right|} \qquad (16b)$$

In the context of Eq. (16), $I_{\text{urb}}^t \neq I_{\text{urb}}^0$ and $I_{\text{tra}}^t \neq I_{\text{tra}}^0$ mean that the implementation of transportation planning comes into effect and the performance of two components are generally enhanced over a certain development period. Obviously, θ =1 or -1 that helps check whether the performances of the transportation network are adapted to the demand of the social and economic development in the form of the similar increasing or decreasing trend during the period of 0 ~ *t*.

4. Results and Findings

4.1 Single Variable Assessment

By Eqs. (1) – (2), the single variable in each domain is normalized into a comparable standardized value. The deviation of a given variable in any domain could be counted out and the weight vectors of domains are to be acquired by Eq. (4). Consequently, the performances of the 8 domains are quantitatively evaluated by Eq. (5), respectively, as shown in Figure 1.

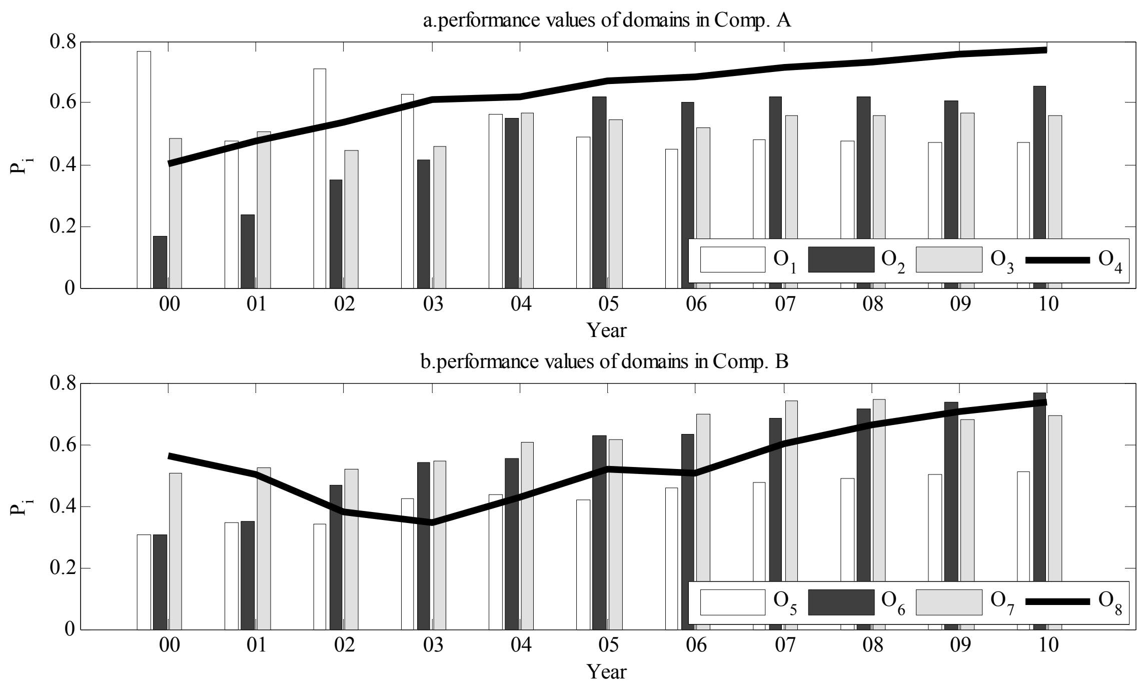

Figure 1. Performances of eight evaluation domains.

Clearly, we can see most performance domains experienced an increasing process during 2000-2010. However, the scores of social development declined year by year and, more seriously, the yearly performance of this domain scored under 0.5 after 2005, which provides an urgent alarm to promote the social equality and balance of resources, income and wealth. Moreover, the life quality domain scored much lower than expected, due to the inflation of currency, and most interviewers feel the increasing burdens of daily expenditures. We also see a significant improvement in the ecological environment.

The transportation network plays an important role in promoting the development of society and economy. The transportation network has made a significant progress in Beijing metropolitan region, especially when it comes to public transport (BRT system, low bus and subway fares, etc.). As for the domains of O_5 ~ O_8, the measured performance values also increased over these years, and the performance score of efficiency even reached 0.7687 in 2010. But the reliability of the transportation network still scored below 0.52, and this could be because of the lack of effective use of the present transportation network and facilities. Moreover, both operation and safety scored under 0.74 and have a great scope for further improvement.

4.2 Estimation of Domain Weight

The performance of components A and B can be perceived and measured through the weighted integration of domains using Eq. (15), and the domain weights are approximated by the approach of analytic hierarchy process. Firstly, a total of 25 cross-country representations with 5 in Beijing, 3 in Xi'an, 2 in Nanjing, 6 in Harbin, 3 in Shenzhen, 4 in Dalian and 2 in Kunming were invited to participate in an interview through email and provide the relative importance of values in the upper triangular matrix $R_{\text{urb, trans}} = R^{4\times4} = [r^{4\times4}]$. The selected interviews are distributed among the three levels: five interviews with planning agencies, four with planning practitioners, seven with manager groups (e. g., governmental departments, traffic management, transit companies.), and nine interviews with normal travelers and system users (different occupations, age, orientation and income).

A survey and a brief description of it were appended to the interviews, including the goals, contents, and standards. All interviews were recorded. In the end, 4 individuals did not respond to the invitation and a total of 3 did not give the judging value among the rest 21 responses, thus a total of 18 valid samples were received.

Component	A	B
Matrix	R^0_{urb}	R^0_{trans}
A	$\begin{bmatrix} 1 & 3 & 4 & \frac{1}{2} \\ \frac{1}{3} & 1 & 2 & \frac{1}{3} \\ \frac{1}{4} & \frac{1}{2} & 1 & \frac{1}{5} \\ 2 & 3 & 5 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & \frac{1}{2} & 1 & 3 \\ 2 & 1 & \frac{1}{3} & 4 \\ 1 & 3 & 1 & 5 \\ \frac{1}{3} & \frac{1}{4} & \frac{1}{5} & 1 \end{bmatrix}$
$\lambda^0_{\max}$	4.0566	4.2895
CI^0	0.0210	0.1084
RI	0.89	0.89
CR	0.0236 < 0.1	0.1218 > 0.1

Table 5. Domain matrixes and consistency.

Then we obtained two pair comparison matrixes R^0_{urb} and R^0_{tra} (see Table 5) after synthesizing each expert's opinion [19]. For Component A, the check of CI = 0.0236 < 0.1 and $a_{ij} \neq a_{ik} / a_{jk}$ means the consistency of matrix R^0_{urb} was acceptable. By Eq. (7), R^0_{urb} was divided into a diagonal matrix D and two unitary matrixes U and V in the form of UDV^T:

Thus, the weight of R^0_{urb} yields W_{urb} = [0.2762, 0.1372, 0.0861, 0.5005]^T [19].

Unfortunately, the paired comparison matrix R^0_{tra} of Component B is inconsistent, and needs to improve its consistency through modifying the element in matrix. From Table 5, we can see $\lambda_{\max}$ = 4.2895, and the corresponding eigenvector W^0_{tra} = [0.2343, 0.2708, 0.4248, 0.0702]^T. Subsequently, the distance between each normalized column vector e_i and W^0_{tra} could be determined by Eq. (12) as d_i = [0.2432, 0.3377, 0.2756, 0.0793]^T. Obviously, the second column e_2 has the longest distance to W^0_{tra}. Then the distance between the normalized e_2 = [0.1053, 0.2105, 0.6316, 0.0526]^T and W^0_{tra} is recalculated and we reach [0.5506, 0.2227, 0.3274, 0.2507]^T [19]. Therefore, e_{21} is the significant element to be modified.

According to Eq. (14), the average $\bar{e}_{21}$ is $\frac{1}{4}\sum_{j=1}^{4}\frac{e_{2j}}{e_{1j}} = \frac{1}{4}\left(\frac{2}{1}+\frac{1}{\frac{1}{2}}+\frac{\frac{1}{3}}{1}+\frac{4}{3}\right) = 1.4167$, and could be further approximated as $e^*_{21} = \frac{1}{2}\left(\bar{e}_{21}+\frac{1}{\bar{e}_{21}}\right) = \frac{1}{2}\left(1.4167+\frac{1}{1.4167}\right) = 1.0613$ and thus e^*_{12} is revised into 0.9422. Obviously, the modified matrix has CR = 0.0578 < 0.1 with satisfied consistency (Table 6). In the end, the weight vector of Component B is determined as W^1_{tra} = [0.2731, 0.2303, 0.4227, 0.0739]^T accounting to $\lambda^1_{\max}$=4.1544 .

$$R^0_{\text{urb}} = \begin{bmatrix} -0.6039 & -0.7571 & 0.2452 & -0.0442 \\ -0.2675 & -0.0959 & -0.8914 & 0.3531 \\ -0.1369 & 0.0554 & -0.3337 & -0.9310 \\ -0.7382 & 0.6438 & 0.1843 & 0.0808 \end{bmatrix} \begin{bmatrix} 8.4366 & 0 & 0 & 0 \\ 0 & 0.7013 & 0 & 0 \\ 0 & 0 & 0.3956 & 0 \\ 0 & 0 & 0 & 0.0107 \end{bmatrix} \begin{bmatrix} -0.2612 & 0.7307 & 0.5894 & 0.2244 \\ -0.5171 & -0.5819 & 0.5819 & -0.2355 \\ -0.8035 & 0.0774 & -0.5415 & 0.2349 \\ -0.1371 & 0.3485 & -0.1440 & -0.9160 \end{bmatrix}^T$$

R_{tra}^{1}	CI^1	RI^1	n	CR^1
$\begin{bmatrix} 1 & 0.9422 & 1 & 3 \\ 1.0613 & 1 & \frac{1}{3} & 4 \\ 1 & 3 & 1 & 5 \\ \frac{1}{3} & \frac{1}{4} & \frac{1}{5} & 1 \end{bmatrix}$	0.0514	0.89	4	0.0578 < 0.1

Table 6. Consistency improvement items of $R_{tra.}$

4.3 TAPI Measure Determination

As soon as the determination of the domain weights had been performed, we yielded the weighted combination Iurb and Itra yearly by Eq. (15) as performances of multiple social and economic development in urban metropolitan region and operations of transportation network, as Figure 2 shows. Obviously, the inflection point appeared in 2006 and 2009. The performance of the transportation network scored below that of the urban system over 2000-2006 because of the accelerated urbanization along with the explosive economic growth. With the coming of the 2008 Beijing Olympic Games, the government invested billions of dollars to increase the capacity and service of airports, transit systems and major roads, especially safer and more efficient subway lines, which helped to improve the overall performance; however, the operation performances of these two systems tended to take a "balanced" approach in 2009 and 2010, and they got approximately the same score.

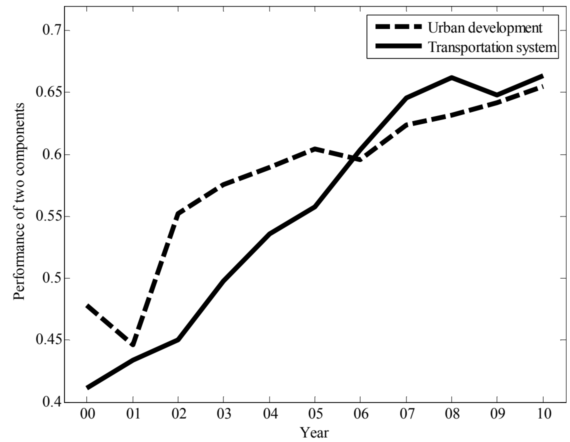

Figure 2. Performances of both Components A and B.

Thereafter, the transportation adaptability performance index and θ over 2000–2010, which are derived from Eq. (16), are expressed in terms of

$$\begin{bmatrix} API \\ \theta \end{bmatrix} = \begin{bmatrix} 0.725 & 0.150 & 2.078 & 2.779 & 1.437 & 5.337 & 1.503 & 1.948 & 1.378 & 1.157 \\ -1 & 1 & 1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \end{bmatrix}$$

It is obvious that the change of the *TAPI* value has undergone a similar regulation or feature over time, as shown in Figure 2. In addition, $TAPI_{01\text{-}02}$ measured in 0.150 implies that transportation infrastructure construction and maintenance were lagged behind the requirement of modern social-economic development. This could be explained through the poor transportation network in reliability, efficiency, operation and safety performance caused by few care policies and limited investment within these years. However, the oversize values of $TAPI_{02\text{-}03}$, $TAPI_{03\text{-}04}$ and $TAPI_{05\text{-}06}$ also indicate that deep concerns have arisen and extensive investment has been made. When transport systems are efficient, they provide economic and social opportunities eventually; at the same time, excessive measures, however, can also bring unavoidable and sharp change in transportation performance, such as the significant increasing of $TAPI_{05\text{-}06}$.

5. Conclusions

This paper discusses the procedure and findings from research that lead to develop a quantitative methodology and tool for metropolitan transportation agencies to quantify and evaluate the performance of transportation plans during the implementation process. The research is applied to the Beijing metropolitan region as an illustrative study. 50 performance variables linked to social, economic and environmental goals are developed and divided into 8 domains in 2 components, and a weighted multi-criteria combination methodology is used to measure the adaptability index values of different periods, in which the domain weight is estimated from the paired comparison matrix with acceptable consistency through the singular value decomposition approach. Specially, the paired comparison matrix is improved by the modification of the significant element, if its consistency is unacceptable. This methodology is implemented in the form of a user-friendly analysis tool for transportation planning practitioners and can help find the potential problems in transportation plans, implementation processes and fund allocations over a much broader scope and agenda.

There are some important notes from this study and it is very important, but very difficult, to choose and process the effective performance variables over a long period of time for trends. Thus, it is recommended that future research lies in exploring an intelligent data processing technique. How can bridge transportation planning and implementation process be reengineered to be conducted within a multidisciplinary set of perspectives (e.g., energy use, traffic equity, community development)? There is a need for continued or more in-depth discussion on certain topics.

The findings and results show that to promote the transportation planning systematically, whether as a strategy for achieving sustainable urban goals or for other items, a policy maker should recognize the demands from different stakeholders [24]. As for metropolitans in China, more attention has been paid on road expansion and facilities construction as well as on the social (economic) environment improvement; however, the physical environment and human oriented transportation issues have been always neglected, just as in the capital Beijing, characterized by low performance of variables in the ecological environment and traffic opinions. Although it may be one of the most challenging issues to solve, it is apparent that the authority in charge of implementing the plans must have a better understanding and make emphasis on setting up new planning projects. At this stage, the most urgent need is to establish stronger connections between transportation and the urban system; this has not yet been accepted by national metropolitan planning organizations, state transportation agencies, and local counties in China.

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