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Multicriteria high-speed rail route selection: application to Malaysia's high-speed rail corridor prioritization

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This paper reviews the literature on multicriteria decision analysis in transportation and provides a case study of high-speed rail (HSR) corridor/route selection using multicriteria methods in the context of HSR corridor prioritization in Malaysia. Using the screening method proposed by Hagler and Todorovich and the ELECTRE I multicriteria method, it is found that the southbound corridor from Kuala Lumpur to Singapore has the highest priority, followed by the eastbound corridor to Kuantan, and northbound to Georgetown. HSR trains could potentially reduce the trip times to Singapore, Kuantan, and Georgetown from Kuala Lumpur, as compared to driving, by 65–73%. The results of this study can be used to assist in the planning of HSR and/or integrated transportation systems in Malaysia. The same methods can be used to evaluate potential HSR corridors/routes in other countries or regions.

Keywords: high-speed rail; route selection; multicriteria analysis; Malaysia

Introduction

High-speed rail (HSR) developments worldwide have been motivated by the need for a more efficient and effective mode of transportation due to population and economic growth, greater environmental awareness, anticipation that HSR development will spur the economy, and/or reducing the dependence on oil (Schwieterman and Scheidt 2007). During the design of a new HSR corridor, a very important aspect to ensure the financial sustainability of the high-speed line is route selection. Route planning is based on some strategic decisions, including passengers' travel demand, station settings, operating capacities, and other planning parameters (Niu et al. 2010). Therefore, it depends on multiple factors and there are possibly some different solutions to the same problem.

Multicriteria evaluation techniques provide a set of tools to analyze and compare the different alternatives for a transport route. A large number of multicriteria methods have been developed and applied to different problems, and many of them are used in different countries to select the best route for a new, big transportation system such as HSR (Anton and Grau 2004; Chang, Yeh, and Shen 2000; Janic 2003; Mateus, Ferreira, and Carreira 2008; Tsamboulas, Yiotis, and Panou 1999; Vreeker, Nijkamp, and Ter Welle 2002). This paper provides an overview of the existing literature on multicriteria decision analysis in transportation and presents a case study of HSR corridor/route selection using multicriteria methods in the context of HSR corridor prioritization in Malaysia.

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Multicriteria decision analysis for assessment of transport projects

Tsamboulas, Yiotis, and Panou (1999) compare the most commonly used multicriteria methods in the assessment of transport projects. These include the Regime criteria (Hinloopen, Nijkamp, and Rietveld 1983; Nijkamp, Rietveld, and Voogd 1990) and the ELimination and Choice Expressing REality (ELECTRE) (Roy 1985; Schaerlig 1985; Szidarovsky, Gershon, and Duckstein 1986) methods, multiple attribute utility approach (Schaerlig 1985), analytical hierarchy process (Saaty 1980), and ideal point approach or the Attribute-Dynamic Attitude Model (ADAM) method (Zeleny 1982). Marler and Arora (2004) present a comprehensive review of multi-objective optimization concepts and methods in engineering.

Hagler and Todorovich (2011) present a screening methodology to prioritize HSR corridors in the USA by evaluating 27,000 city pairs and identifying the top city pairs for HSR development. The study proposed a set of six criteria – metropolitan/population size, economic productivity, distance, transit connections, mega region location, and level of congestion. The basis of their evaluation process was as follows:

- a preference for cities with larger populations in large metropolitan areas over cities with smaller metropolitan areas,
- that HSR is more competitive when compared to other modes at distances between 100 miles (161 km) and 500 miles (805 km),
- a preference for metropolitan areas with existing transit systems,
- a preference for city pairs with higher combined per capita gross domestic product (GDP),
- a preference for cities with higher highway and airport congestion levels, and
- a preference for cities located in mega regions – that is, a network of metropolitan regions with shared economies, infrastructure, and natural resource systems stretching over 300 miles (483 km) to 600 miles (966 km) in length.

Another example of a multicriteria analysis to select a route for HSR is presented in Anton and Grau (2004). The authors use the ELECTRE I method to select the HSR route between Madrid and Valencia in Spain. Three alternative routes and four basic criteria were proposed to compare them – cost, trip duration, potential users, and environmental index. Unlike the methodology presented in Hagler and Todorovich, Anton and Grau had already selected the cities to be linked – Madrid and Valencia – so the next step was to select the best HSR route. An attempt to access many cities along the same route was shown to be detrimental because it made the trip too long and less attractive for people to take the HSR.

HSR corridor prioritization in Malaysia

In this section, a case study is presented to illustrate the use of the multicriteria methods discussed in the previous section. The case study is focused on the selection process of potential corridors/routes for a HSR system in Malaysia. The first phase of the analysis is an origin-to-destination (O–D) analysis, and the second phase is an analysis taking into account all the cities along the corridor using the ELECTRE I method.

Malaysia is located in Southeast Asia and has two main regions – Peninsular Malaysia (West Malaysia) and Malaysian Borneo (East Malaysia) (Figure 1). This case study focuses on potential HSR development in Peninsular Malaysia. In 2010, the total population in Malaysia was over 28 million, with over 22 million or about 80% of the total population

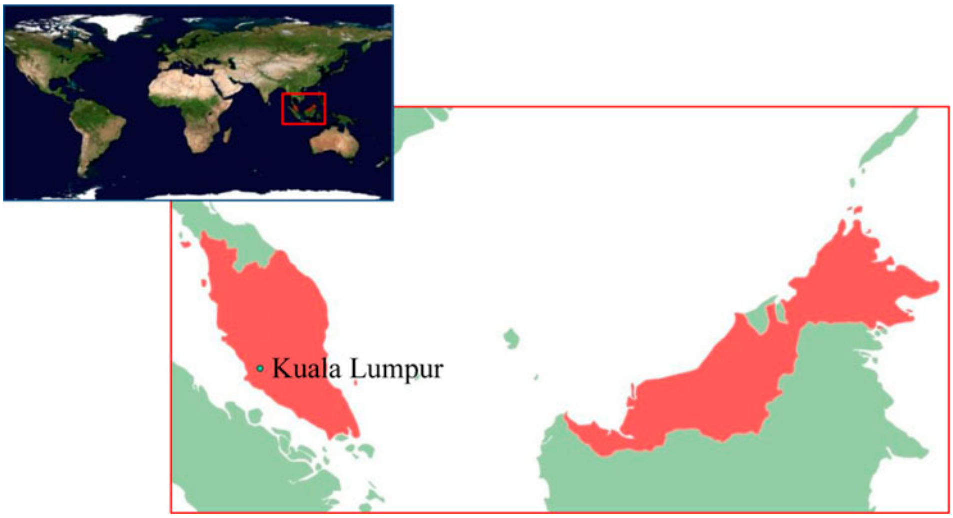

Figure 1. Malaysia territory.

living in Peninsular Malaysia. Located between 2 and 7 degrees north of the Equator, Peninsular Malaysia is separated from Malaysian Borneo by the South China Sea. To the north of Peninsular Malaysia is Thailand while its southern neighbor is Singapore. The capital city of Malaysia is Kuala Lumpur (Malaysian Department of Statistics 2012).

In 2010, Malaysia's GDP was US$414 billion, the 3rd largest economy in the Association of Southeast Asian Nations (ASEAN) and 29th largest in the world. Its GDP grew by 7.2% in 2010 and 5.1% in 2011 (Wikipedia 2012a). Some other aspects, besides a strong economy, that make Malaysia a prime candidate to develop a HSR system are the relatively weak rail infrastructure in comparison with the road infrastructure, and the concerns about sustainable development and energy efficiency. Also, the population is concentrated in dense cities along natural corridors in Peninsular Malaysia, and the existence of developed and planned transportation systems could help foster the success of a HSR system.

Malaysia can also utilize its advantage as the closest country to Singapore, a city–state country with the third highest GDP per capita in the world, as well as one of the five busiest ports, one of the four most important financial centers, and a prime location for international business (Wikipedia 2012b). In this case study, the effect of including Singapore in the selection process of HSR in Malaysia will be shown.

An origin-to-destination (O–D) analysis

The methodology presented in Hagler and Todorovich (2011) was used to identify high-potential city pairs to be connected by a HSR system in Malaysia. Specifically, three out of their six criteria – metropolitan/population size, economic productivity, and distance – were used to rank the pairs or main cities in Malaysia. The other three criteria – transit connections, mega region, and congestion – were not considered due to the unavailability of publicly available data. The cities evaluated in this analysis are shown in Table 1 with their populations and GDP per capita. Figure 2 shows the location of these cities in Peninsular Malaysia.

The population index was calculated as the sum of the index for each city in an O–D pair, as shown in Table 2. The GDP index is shown in Table 3, based on the geometric

Table 1. Malaysian cities, population, and GDP per capita.

Province	Population	Per capita GDP (RM)	Per capita GDP (US$)
Kangar	225,590	15,296	9985
Alor Setar	405,523	13,294	8678
Pulau Pinang	708,127	33,456	21,840
Ipoh	657,892	16,088	10,502
Kuala Lumpur	1,588,750	55,951	36,525
Seremban	314,502	27,485	17,942
Melaka	484,885	24,697	16,122
Johor Bahru	497,067	20,911	13,651
Kuantan	427,515	22,743	14,847
Kuala Terengganu	337,553	19,225	12,550
Kota Bharu	314,964	8273	5401

Source: Malaysian Department of Statistics (2012).

Figure 2. Cities of Malaysia (the different sizes of dollar sign and circle reflect the relative differences in GDP and population size, respectively).

Table 2. Population index.

Population in a city	Index
Under 100,000	0
100,000–500,000	1
500,000–1,500,000	2
More than 1,500,000	3

Table 3. GDP index.

Geometric mean of GDP for an O–D city pair	Index
Under 20,000	0.0
20,000–30,000	0.5
30,000–40,000	1.0
40,000–50,000	1.5
50,000–60,000	2.0
More than 60,000	2.5

mean of GDP between two cities in an O–D pair. The distances between each pair of cities shown in Figure 3 were estimated based on the current rail lines in Malaysia, or the highway if there was no rail line. Table 4 presents the estimated distances between each pair of cities considered in this analysis. The distance index shown in Table 5 was calculated based on the formulae from Hagler and Todorovich (2011) and illustrated in Figure 4.

The total index was calculated as the sum of these three indices. Once the total index for each pair of cities was calculated, the highest index value was set to a value of 10 points and the rest were normalized proportionally. Finally, a ranking was developed based on the final score for each O–D pair. Table 6 shows the ranking with the 10 highest index scores and associated city pairs. Note the importance of HSR to connect from/to the capital city, Kuala Lumpur, reflected in the fact that the city is shown in the top nine O–D city pairs. The top potential O–D pair for HSR implementation is between Kuala Lumpur and Georgetown, Penang.

As alluded to before, the influence of Singapore in planning HSR in Malaysia could be very important. Consequently, the analysis was repeated by including Singapore. Table 7 shows the ranking of city pairs when connectivity with Singapore is considered.

When Singapore is considered, the top potential O–D pair for a HSR implementation is between Kuala Lumpur and Singapore, followed by Kuala Lumpur and Georgetown. Figure 5 shows the total score comparisons when Singapore is excluded and included. In essence, the use of the multicriteria method from Hagler and Todorovich (2011) serves as a screening process to identify major, potential HSR corridors in Malaysia. Based on this analysis, the main corridors identified are from Kuala Lumpur: (1) northbound to Georgetown, (2) eastbound to Kuantan, and (3) southbound to Singapore. The following subsections consider the three corridors and rank order them using the ELECTRE I method.

Figure 3. Potential HSR route alignments in Malaysia.

HSR corridor analysis using the ELECTRE I method

The ELECTRE I method, also known as concordance analysis, is based on a pairwise comparison of all alternatives. In a multicriteria problem, the prevalence of one alternative over another can be determined only when there is a consensus of points of view. Therefore, one alternative would be better than another different alternative when the first is at least as good as the second when assessed against all criteria considered. This model uses the notions of concordance and discordance to describe when an alternative is superior or inferior to another alternative (Tsamboulas, Yiotis, and Panou 1999).

Using the ELECTRE I method, a decision-maker primarily determines the concordance and discordance limits, compares all pairs of alternatives for valid outranking relations, and computes the positive and negative flows. Final rankings are calculated on the basis of the intersection of these flows.

In the context of HSR corridor/route prioritization in Malaysia, the following alternatives were considered:

A1: Kuala Lumpur – Ipoh – Georgetown (northbound alternative): the first alternative links the two major cities/regions in Malaysia – Kuala Lumpur and Georgetown. It also includes Ipoh, a city midway between Georgetown and Kuala Lumpur. With a total length of 238 miles (383 km), it is in the range of distances where a HSR is considered competitive. This alternative is shown in Figure 6.

A2: Kuala Lumpur – Kuantan (eastbound alternative): this alternative connects Kuala Lumpur with Kuantan with a total length of 148 miles (238 km). This alternative is also shown in Figure 6.

Table 4. Distance between city pairs.

	Kangar	Alor Setar	Pulau Pinang	Ipoh	Kuala Lumpur	Seremban	Melaka	Johor Bahru	Kuantan	Kuala Terengganu	Kota Bharu
(a) In miles											
Kangar	–	–	–	–	–	–	–	–	–	–	–
Alor Setar	30	–	–	–	–	–	–	–	–	–	–
Pulau Pinang	94	64	–	–	–	–	–	–	–	–	–
Ipoh	196	166	113	–	–	–	–	–	–	–	–
Kuala Lumpur	322	292	239	126	–	–	–	–	–	–	–
Seremban	366	335	282	169	43	–	–	–	–	–	–
Melaka	412	381	328	215	89	46	–	–	–	–	–
Johor Bahru	545	514	461	348	222	179	171	–	–	–	–
Kuantan	470	440	386	273	148	191	209	272	–	–	–
Kuala Terengganu	583	552	499	386	260	304	322	385	113	–	–
Kota Bharu	626	595	542	429	303	347	364	428	207	94	–
(b) In kilometers											
Kangar	–	–	–	–	–	–	–	–	–	–	–
Alor Setar	49	–	–	–	–	–	–	–	–	–	–
Pulau Pinang	151	102	–	–	–	–	–	–	–	–	–
Ipoh	316	267	182	–	–	–	–	–	–	–	–
Kuala Lumpur	519	470	384	202	–	–	–	–	–	–	–
Seremban	588	540	454	272	70	–	–	–	–	–	–
Melaka	662	614	528	346	144	74	–	–	–	–	–
Johor Bahru	877	828	742	560	358	288	275	–	–	–	–
Kuantan	756	707	622	440	238	308	336	438	–	–	–
Kuala Terengganu	938	889	803	622	419	489	517	620	181	–	–
Kota Bharu	1007	958	872	690	488	558	586	689	333	152	–

Table 5. Distance index.

Distance between an O–D city pair (D, in miles)	Index formula
Under 150 miles	$D/100 + 1$
150–300 miles	2.5
300–350 miles	$(500-D)/100 + 0.5$
350–500 miles	$(500-D)/75$
More than 500 miles	0

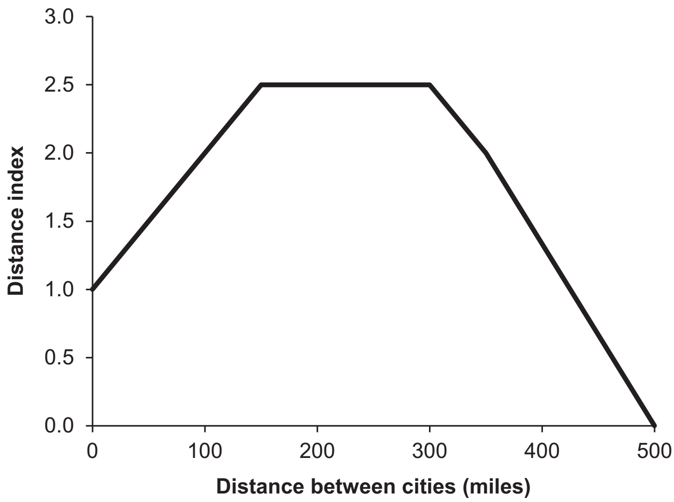

Figure 4. Distance between an O–D city pair (miles) versus distance index.

Table 6. Ranking of city pairs.

Order	O–D city pair		Normalized score
1	Georgetown	Kuala Lumpur	10.00
2	Ipoh	Kuala Lumpur	9.07
3	Kuala Lumpur	Johor Bahru	8.75
4	Kuala Lumpur	Kuantan	8.75
5	Kuala Lumpur	Kuala Terengganu	8.75
6	Alor Setar	Kuala Lumpur	8.13
7	Kuala Lumpur	Kota Bharu	8.08
8	Kuala Lumpur	Melaka	7.99
9	Kangar	Kuala Lumpur	7.85
10	Georgetown	Ipoh	7.66

A3: Kuala Lumpur – Seremban – Johor Bahru – Singapore (southbound alternative): the third alternative links Kuala Lumpur and Singapore, the two most important cities in the region. Also, this line passes through Seremban and Johor Bahru, two cities that could benefit by the presence of the HSR system. The total distance is 242 miles (389 km). This alternative is also shown in Figure 6.

Table 7. Ranking of city pairs when Singapore is considered.

Order	O–D city pair		Normalized score
1	Kuala Lumpur	Singapore	10.00
2	Georgetown	Kuala Lumpur	8.00
3	Ipoh	Kuala Lumpur	7.26
4	Seremban	Singapore	7.00
5	Melaka	Singapore	7.00
6	Kuantan	Singapore	7.00
7	Kuala Lumpur	Johor Bahru	7.00
8	Kuala Lumpur	Kuantan	7.00
9	Kuala Lumpur	Kuala Terengganu	7.00
10	Ipoh	Singapore	6.83

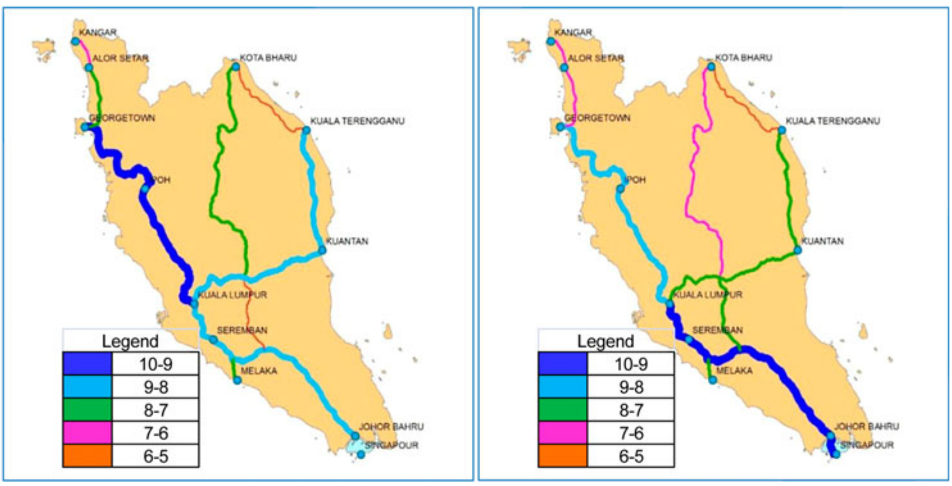

Figure 5. Total score comparisons when Singapore is excluded (left) and included (right).

The following criteria were used in this analysis:

- Construction cost: a typical HSR cost per double-track mile of US$90 million was assumed.
- Potential users: the sum of the population of every city on a line.
- GDP: the geometric mean of the GDP of every city on a line.

Table 8 shows the basic information for this decision problem. Note that a weight of 1 was assigned for cost and 2 for potential users and GDP. This reflects the short-term impact of cost, mainly during the HSR construction period, as compared to the impacts of potential users and GDP that affect the ridership throughout the life of the HSR system. Also, index n_j is positive for a criterion when more is better for the criterion, and vice versa.

Figure 6. Alternative HSR corridors considered using the ELECTRE I method.

A concordance index matrix C (shown in Table 9) was then computed by comparing between pairs of alternatives, and accounting for the criteria's weights. This matrix is defined as follows:

$$C_{ik} = \sum_{j=1,2,3} \delta_{jik} w_j \quad \text{where } \delta_{jik} = \begin{cases} 1 \ \textit{if} \ n_j\left(I_{ij} - I_{kj}\right) > 0 \\ \frac{1}{2} \ \textit{if} \ I_{ij} = I_{kj} \\ 0 \ \textit{if} \ n_j\left(I_{ij} - I_{kj}\right) < \mathit{0} \end{cases}$$

In order to calculate the discordance matrix D, the standardized and weighted matrix T (Table 10) was first determined. In this matrix T, each element is defined as the value of

Table 8. Basic information for ELECTRE I analysis.

	Cost (US$), j = 1	Potential users, j = 2	GDP region (US$), j = 3
A1 (northbound from Kuala Lumpur)	21,491	2,954,769	20,310
A2 (eastbound from Kuala Lumpur)	13,293	2,016,265	23,286
A3 (southbound from Kuala Lumpur)	21,752	6,189,619	25,876
Weights, w_j	1	2	2
Index, n_j	−1	1	1

Table 9. Concordance table.

C_{ik}	A1	A2	A3
A1		2	1
A2	3		1
A3	4	4	

Table 10. Standardized and weighted matrix *T*.

T_{ij}	Cost	Users	GDP
A1	2.540	1.416	7.297
A2	1.571	0.966	8.366
A3	2.571	2.966	9.297

the criterion j for an alternative divided by the difference between the maximum and the minimum values of criterion j for all alternatives, and multiplied by the weight w_j.

A discordance matrix D (Table 11) was then calculated using the following definition:

$$D_{ik} = \frac{Max\left(Max\left(T_{kj} - T_{ij}\right)n_{\mathrm{j}}, 0\right)}{Max\left(\left|T_{ij} - T_{kj}\right|\right)} \quad \text{with } j = 1, 2, 3$$

Finally, an aggregated matrix A (Table 12) shows the final result of the ELECTRE I method. This matrix is defined as $A_{ik} = 1$ when $C_{ik} > C_T$ and $D_{ik} < D_T$, i.e. the alternative

Table 11. Discordance matrix.

D_{ik}	A1	A2	A3
A1		1.000	1.000
A2	0.421		1.000
A3	0.015	0.500	

Table 12. Aggregate matrix.

A_{ik}	A1	A2	A3
A1		0	0
A2	1		0
A3	1	1	

A_i is better than alternative A_k. The values C_T and D_T are the average of the concordance and discordance matrixes, in this case $C_T = 2.5$ and $D_T = 0.656$.

Table 12 shows that Alternative A3 (southbound from Kuala Lumpur to Singapore) is better than the other two alternatives, and Alternative A2 (eastbound from Kuala Lumpur to Kuantan) is better than Alternative A1 (northbound from Kuala Lumpur to Georgetown). Consistent with the results when the methodology from Hagler and Todorovich (2011) was used, the best alternative corresponds to the corridor linking Kuala Lumpur and Singapore. This alternative has the greatest number of potential users and total GDP. Alternative A2 is better than Alternative A1 because of the lower construction cost and higher total GDP.

Discussion and conclusions

This paper has illustrated the use of multicriteria methods in the selection process of potential corridors/routes for HSR in Malaysia. The use of the approach – presented in Hagler and Todorovich (2011) – focuses on the potential ridership between two cities based on the size of their populations, economic activity, and distance and serves as a screening process to identify major, potential HSR corridors in the country, namely from Kuala Lumpur (1) northbound to Georgetown, (2) eastbound to Kuantan, and (3) southbound to Singapore.

The three corridors were then evaluated and rank ordered using the ELECTRE I method that considers both ridership and cost. It was found that the southbound corridor from Kuala Lumpur to Singapore has the highest priority, followed by the eastbound corridor to Kuantan, and northbound to Georgetown. Note that in the ELECTRE I analysis, a uniform unit cost was used for all alternative corridors. More detailed engineering analyses may reveal a higher cost for the eastbound alternative from Kuala Lumpur to Kuantan as it has a challenging terrain that may require extensive tunneling to access the east coast of Peninsular Malaysia. However, developing a better, advanced transportation system may significantly help to spur the economy of the east coast region. Collectively, assuming an average HSR operating speed of 174 mph (280 km/h), HSR trains could reduce trip times to Singapore, Kuantan, and Georgetown, as compared to driving, by 65–73% (Figure 7).

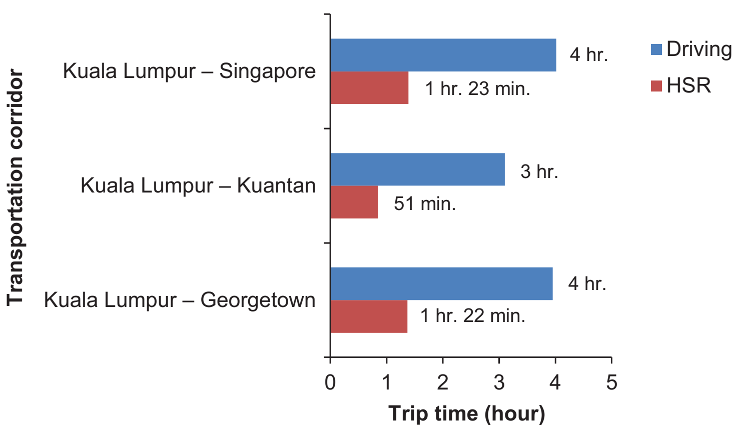

Figure 7. Trip time comparisons between driving and HSR.

More comprehensive HSR feasibility studies are expected to look beyond ridership and construction cost. Other important impacts to consider may include the following categories (Sinha and Labi 2007): technical – such as travel time, operation and maintenance cost, accessibility, mobility and congestion, safety, connectivity with other transportation modes, land use patterns, and risk and vulnerability; environmental – such as air quality, water resources, noise, wetlands and ecology, and esthetics; economic development – such as employment, number of new businesses, GDP, regional economy, and international trade; legal – such as liability exposure; sociocultural – such as quality of life; and economic efficiency – such as life cycle costs and benefits. However, it is considered that the results of the study reported in this paper can be used to assist in the planning of HSR and/or an integrated transportation system in Malaysia. The same methodologies can also be used to evaluate potential HSR corridors/routes in other countries or regions.

Disclosure statement

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