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The carbon savings and health co-benefits from the introduction of mass rapid transit system in Greater Kuala Lumpur, Malaysia

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ABSTRACT

Introduction: Transportation is a convenient way to incorporate an active lifestyle, in addition to reducing environmental pollution. This study estimates the changes in carbon dioxide (CO_2) emissions and the health co-benefits from two new mass rapid transit (MRT) lines in Greater Kuala Lumpur, Malaysia.
Method: Changes in CO_2 and air pollutant emissions were estimated from motor vehicle activity based on the travel information collected from a survey. Health effects were estimated using a comparative health risk assessment method. Exposure to air pollution was modelled based on the reduction in ambient PM2.5 concentration. Traffic injury was estimated using a constant risk per distance for each transport mode. Physical activity was modelled based on the amount of walking to or from the stations. Health outcomes were calculated as changes in premature deaths and disability adjusted life years (DALYs).
Results: The two MRT lines would reduce 337,800 t of CO_2 equivalent per year from private transportation. However, the use of motor vehicle in the station access-egress would offset 28% of the total carbon savings. The ambient PM2.5 concentration would be reduced by 0.12 $\mu g/m^3$, preventing 5 deaths and 104 DALYs per year. Reduced traffic injuries would prevent 88 deaths and 6300 DALYs per year, while increased walking would prevent 90 deaths and 3200 DALYs per year. Sensitivity analysis revealed that travel distance, modal shift and station access-egress distance could considerably change CO_2 emission reduction, while relative risks of physical activity could significantly affect attributable burden of diseases.
Conclusion: The two MRT lines would reduce 6% of CO_2 equivalent emission from private motor vehicles in Greater Kuala Lumpur and bring important health co-benefits to the population. However, strategic planning around the MRT stations for access and egress is necessary to achieve maximal benefits.

1. Introduction

Cities are major contributors to global carbon emissions (UN-Habitat, 2011) but are also where the most effective carbon mitigation could be made (Dodman, 2009). As population increases in cities, transport carbon emission will be the fastest growing among

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the energy end-use sectors (Sims et al., 2014). The limited efficient transport choices in developing countries further spurred the rate of emissions from motorization. Although cleaner fuels could help reduce transport emissions, increasing number of motor vehicles has caused emissions to continue to rise (Schipper et al., 2009). Therefore, compared to road expansions which encourage motorization, provision of public transport and other low carbon transport infrastructure could be the more effective way to reduce traffic and prevent future emission lock-in.

Transit infrastructure can reduce carbon emissions by modal shift, congestion relief and land use multiplier (APTA, 2017). The amount of reduction from modal shift depends on the transport activities (vehicle fleet and distance travelled), fuel efficiency (petrol, diesel) and the local driving cycle (acceleration, starting, stopping) (Schipper et al., 2009; Tzirakis et al., 2006). Congestion relief which entails increased speed reduces emissions as fuel efficiency improves. The land use multiplier is characterized by the development of a denser land use pattern and more opportunities to live close to transit stops which then shortens trip distance and reduces the use of private automobiles (APTA, 2017). On the other hand, the construction, maintenance and operation of transit system utilize energy which can produce an amount of emissions depending on the source of power generation. The construction emissions from carbon intensive process such as tunnelling would require a lifetime operation of transit infrastructure to compensate (ADB, 2017).

Previous transport health impact assessment studies have shown substantive public health co-benefits from the adoption of alternative transport systems (Mueller et al., 2015; Shaw et al., 2014). Most health impact modelling and co-benefit studies have emphasized active transport, especially cycling, with less focus on public transport policies (Rojas Rueda et al., 2013; Xia et al., 2015; Woodcock et al., 2014). This could partly be because most studies were done in developed nations where the public transport network is more established. In developing countries where vast urban land and transport planning is still underway, providing evidence on public transport infrastructure may be more important so as to justify the financial allocations and commitments from local governments.

The expansion of Greater Kuala Lumpur (GKL), also known as Klang Valley, in Malaysia has created a large conurbation area. The GKL covers 2793 km^2 with 6.3 million population in 2010, and is projected to reach 10 million population by 2020 (PEMANDU, 2012). It consists of ten local authorities which include part of the neighboring Selangor state. Its national economic importance is clear, contributing 37% of the Gross Domestic Product of Malaysia (SPAD, 2013). The urban expansion has propelled the use of motor vehicles to travel into the city. In view of this, the Kuala Lumpur City Hall is striving to increase public transport modal share from 21% to 40% by 2030 (SPAD, 2014; Eleventh Malaysia Plan, 2015). In the Greater Kuala Lumpur Land Public Transport Master Plan (SPAD, 2013), urban rail will be the future spine of public transport network in the city. Currently, the GKL is served by two light rail transit (LRT) lines and a monorail for the urban areas, and Keretapi Tanah Melayu (KTM) commuter train and airport express for the suburban areas. The metro mass rapid transit (MRT) infrastructure is one of the largest transport infrastructure projects in Malaysia. Three MRT lines costing RM80 billion (USD 20 billion) have been proposed for the integrated urban rail network. The first MRT line is 51 km and runs from the northwest to the southeast corridor (Sungai Buloh-Kajang (SBK)) of GKL with 31 stations (Fig. 1.). The second MRT line will be 52 km and runs from the northeast to the southwest corridor (Sungai Buloh-Serdang-Putrajaya (SSP)) with 37 stations. The first line is estimated to fully open by 2017 and the second line by 2022. The third line is still being planned.

The aim of this study is to quantify the potential emission reduction and health co-benefits through modal shift from the two upcoming MRT lines in GKL. We quantified the changes in CO_2 equivalent and air pollutant emissions from the private motor vehicles that would shift to the MRT system, and the subsequent changes in premature mortality and morbidity from air pollution, traffic injuries and physical activity. This study differs from the preliminary results on mortality avoidance presented in Kwan et al. (2016) as this study uses more recent emission factors and primary trip data from a travel survey in the calculations. Besides, we also included the future MRT (SSP) and the contribution of private motor vehicle use in the access and egress of the MRT stations in the estimation of total emissions and health co-benefits.

2. Method

2.1. Conceptual framework

A travel survey was conducted to collect data on existing travel characteristics of the local population. The travel data was then fed into the calculation of emission savings and health co-benefits. Fig. 2. shows the conceptual framework for this study. The MRT system is expected to cause modal shift from private motor vehicles and create induced trips. Induced trips are defined as the additional trips travelled that would be made when travel conditions such as transport infrastructure improves (Cervero, 2003; Gorham, 2009). The analysis further separated trips into the line haul and station access-egress. The line haul is the rail journey distance from home stations to destination stations while the access-egress is the pathway to or from the station at the home-end or destination-end. The calculation of impact from line haul excluded that of the induced trips because the induced trips would not be replacing existing private motor vehicle trips. However, there would be additional access-egress trips generated from these induced trips in the scenario with MRT. The access-egress pathway however was accounted for all trips. The overall changes in vehicle kilometres travelled would cause changes in transport CO_2 emissions, air pollutant emissions and road traffic exposure while station access-egress provides increased opportunity for walking. Cycling was not modelled due to low baseline modal share and lack of safe cycling infrastructure.

The health co-benefits included air pollution, traffic injuries and physical activity. This study adopted the comparative health risk analysis method (Ezzati et al., 2004) as applied in the Integrated Transport and Health Impact Modelling (ITHIM) (Woodcock et al., 2013, 2014; Woodcock et al., 2009). The air quality was assessed based on the change in ambient PM2.5 concentration from air

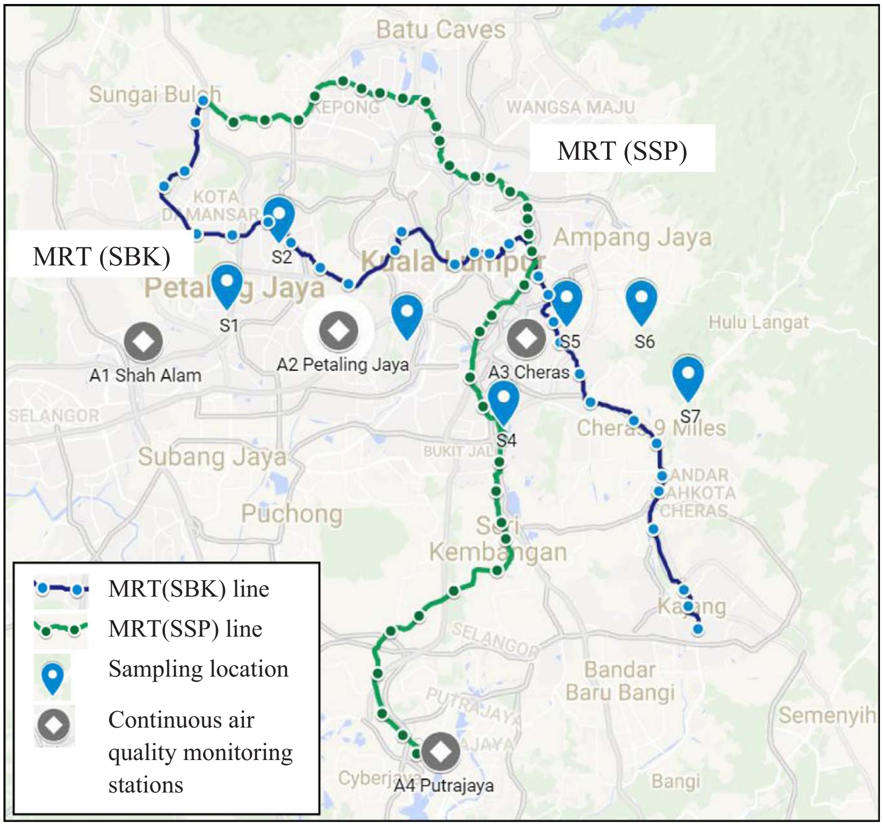

Fig. 1. MRT lines, sampling locations of survey (S1-S7) and continuous air quality monitoring stations (A1-A4) in Greater Kuala Lumpur.

pollutant emissions. The baseline burden of disease data was retrieved from the Malaysian national data in the Global Burden of Disease Study 2010 (GBD, 2013). The disease cause categories included in the health assessment were according to ITHIM as presented in Maizlish et al. (2011) (Table A.1). All the emissions and health co-benefits amount were calculated for 365 days per year. We assumed no lag between the changes in air quality and physical activity, and health.

2.2. MRT ridership and modal shift

The projected ridership for the two MRT lines were derived from the Environmental Impact Assessment (EIA) Report of the respective MRT lines (EIA, 2011, 2015). For the first MRT (SBK) line, there would be 442,000 daily ridership in the opening year of

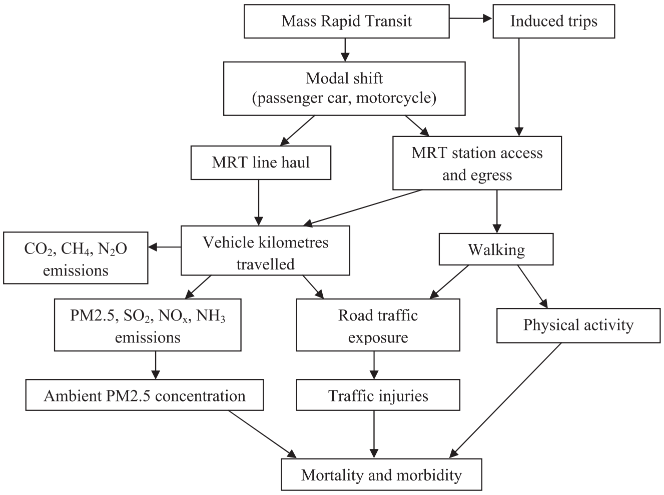

Fig. 2. Conceptual framework.

2017. From the ridership, there would be an expected modal shift of 66% from passenger cars, 33% from motorcycles and 1% from buses. The second MRT (SSP) line would have 533,000 daily ridership at the full commencement in 2022. The amount of modal shift for the MRT (SSP) line was not stated in its EIA report and was therefore assumed to be the same as the MRT (SBK) line. Due to the small percentage of bus modal shift and data limitation, bus was not included in the modelling except for the sensitivity analysis. Although the technical report for the ridership estimation could not be accessed, the figures were considered reasonable when compared to the 190 km Delhi metro with 1.79 million ridership (Doll and Balaban, 2013). Besides, the EIA report had been reviewed by the expert panel required for the approval by the Department of Environment (Department of Environment, 2007).

2.3. Travel data (survey)

A cross sectional travel survey was conducted to get information on the existing travel pattern in the corridor of the MRT (SBK) line only as the stations for the MRT (SSP) line have not been finalized then. The survey areas were chosen by systematically sampling eight out of the 31 planned MRT (SBK) stations to get at least 60 respondents from each station. This was followed by a convenient sampling of survey locations relative to the selected stations. The nearest local supermarkets to the stations were selected as survey locations in order to reach out to the household residents in the vicinity who will be the potential users of the MRT (Fig. 1.). All the respondents were above 18 years old and were approached through intercept method. Most of them ($>$ 90%) were willing to accept the interview on the spot. The study area consisted of residential, commercial, institutional and industrial areas along major road networks (EIA, 2011). All the survey locations in this study were within 5 km from the MRT stations which were then under construction. The survey was carried out between February 2015 and June 2015. All the travel data used in modelling were based on the outcome from the survey.

2.4. Scenario

Changes in CO_2 and air pollutant emissions and health outcomes from the use of the MRT (SBK) and MRT (SSP) were compared against a counterfactual baseline scenario without the MRT lines. The health impacts were estimated using comparative health risk assessment as shown in Eq. (1) (Ezzati et al., 2004). We applied 15% induced trips which were deducted from the full ridership in the modelling of emissions and traffic injuries for line haul. This figure was taken with reference to the Indian metro where 14–18% of its users would not have travelled otherwise (Goel and Tiwari, 2015). Vehicle occupancy were1.6 person per car and 1.3 person per motorcycle based on Malaysian sources (GEF, 2010).

$$PAF = \frac{\sum_{i=1}^{n} P_i RR_i - \sum_{i=1}^{n} P'_i RR_i}{\sum_{i=1}^{n} P_i RR_i} \tag{1}$$

P_i = proportion of population at baseline exposure level, i
P'_i = proportion of population at counterfactual exposure level, i
RR_i = relative risk at exposure level, i
n = number of exposure levels

For trip distance, the median origin-destination distance of current motorised transport users was applied as line haul in the model assuming that the trips would shift to the MRT. For access-egress, the modal share and the ratio of access-egress distance (for those using motorised transport) relative to the origin-destination distance was obtained from the current rail users (LRT and KTM) from the travel survey. The ratio of access-egress distance was based on the concept of interconnectivity ratio by Krygsman et al. (2004). This ratio was then applied on the origin-destination distance of motor vehicle trips that would be replaced by the MRT line haul. All users were assumed to walk an average of five minutes per trip either in the access or egress of stations regardless of modal share. This was due to the large percentage of current riders accessing home-end rail stations by motorised transport and destination-end stations by walking based on the travel survey.

2.5. Emissions of CO_2 and air pollutants

The emissions of CO_2 and PM2.5 air pollutants from the private motor vehicles were calculated with Eq. (2). The magnitude of transport activity in vehicle distance travelled was calculated based on data from the travel survey. The emission factors were derived from a number of external sources which were mostly based in the United Kingdom specifically in the urban areas (Tables A.2 and A.3). For carbon emissions, the amount of CO_2, CH_4 and N_2O emissions were multiplied with their global warming potential (IPCC, 2013) to produce the carbon dioxide equivalents value (CO_2 eq). For PM2.5, direct primary PM2.5 from exhaust and the re-entrained dust from brake wear, tyre wear and road abrasion were calculated. Besides, the emissions of precursor gases of secondary PM2.5 which include SO_2, NO_x and NH_3 were also calculated. Emissions from cold starts of vehicles were calculated by the number of trips (replacing the vehicle kilometres travelled component in Eq. (2)).

$$Total\ emissions = \sum [M_{mode}(VKT_M)\ (EF_M)] \tag{2}$$

M_{mode}: transport mode (passenger car and motorcycle)

VKT_M: vehicle kilometres travelled by vehicle type (km)
EF_M: emission factors for by vehicle type (g/km)

2.6. PM2.5 concentration

The change in air quality was represented by the attributable concentration of PM2.5 from the emission reduction using intake fractions. Taking advantage of the existing model linking emissions to intakes in Kuala Lumpur, the intake fractions were worked backwards to link emission reduction to concentration reduction (Eq. (3)). Intake fraction specific to Malaysian cities from Apte et al. (2012) was used for primary PM2.5. Secondary PM2.5 concentrations from the precursors were based on the generic intake fractions from systematic review by Humbert et al. (2011), and scaled to the location-specific primary intake fraction (Table A.4).

$$PM2.5\ concentration\ (mg/m^3) = (iF\,(ppm)*emissions\,(kg))/breathing\ rate\ (m^3 person^{-1} day^{-1}) \tag{3}$$

The baseline concentration of particulate matter (PM10) was obtained from the averages of continuous air quality monitoring (CAQM) stations close to the MRT lines (Fig. 1.). The stations were Petaling Jaya, Cheras, Shah Alam and Putrajaya. A ratio of 0.6 PM2.5: PM10 was then applied in estimating the baseline PM2.5 concentration. A linear dose response relationship (Ostro, 2004) was used to estimate the health burden from acute respiratory diseases (age < 5), cardio-respiratory diseases (age > 30) and lung cancer (age > 30) (Table A.5). The dose response functions have been consistent with the later evidences (Hoek et al., 2013) and the baseline PM2.5 concentration in Kuala Lumpur was within the applicable range under 30 $\mu g/m^3$.

2.7. Traffic injuries

The baseline rates of road traffic death and injury per vehicle kilometre travelled by mode were calculated from the national road traffic injury data (2010–2013) and vehicle kilometres travelled by mode data (2009) obtained from Malaysian Institute of Road Safety Research (MIROS). The national traffic injury data obtained has been processed with the MIROS Road Accident Analysis and Database System (M-ROADS). The vehicle distance travelled was assumed to be constant through the years. The distribution of vehicle kilometres travelled for each age groups were calculated using vehicle ownership rate per population and applied to the size of the population in each age groups. For pedestrian exposure where walking distance data was not available, the national mean walking minutes in the National Health and Morbidity Survey (2011) urban strata was converted to distance using walking speed applied by Woodcock et al. (2009).

The modelling of road traffic injuries encompassed the reduction in the distance travelled on road by private motor vehicles, and the additional distance travelled by private motor vehicles and pedestrian walking during the access-egress of MRT stations. A constant linear exposure-casualty relationship was applied, with higher risks of casualty with increased kilometres travelled by each transport mode. Each walking trip distance was 0.45 km based on the survey data. The attributable fractions for death and disability years were calculated collectively based on the risks of death and major injury using motor vehicles relative to taking the MRT, including the access-egress trips. The risk of injury during rail trip was not included as urban rail injuries were uncommon in Malaysia (Nordin et al., 2014).

2.8. Physical activity

The change in physical activity level was modelled by adding the increase in metabolic equivalents (MET) hours per week from walking to the background physical activity. Each walking minutes was assigned 3.5 METs at moderate pace (2.8–3.2 mph) based on the Compendium of Physical Activity (Ainsworth et al., 2011). The background physical activity of population in the urban strata of Kuala Lumpur and Selangor was obtained from the National Health Morbidity and Mortality Survey (NHMS) 2006. The amount of physical activity measured in the survey encompassed three life domains: work, leisure and transport. Only the sum of work and leisure activities were taken as the background physical activity. To estimate the impacts for people with low, medium and high background physical activity level, we calculated the impacts with 5th percentile, mean and 95th percentile of the background physical activity distribution.

The relative risks of diseases related to physical activity were based on the ITHIM tool as described elsewhere (Woodcock et al., 2014; Götschi et al., 2015) (Table A.6). The exposure response functions of physical activity were curvilinear by using a power transformation specific to each diseases. As the relative risks for diabetes and cardiovascular diseases were based on background walking only, in this case, activity from the travel domain in NHMS 2006 was used for calculations.

The relative risks for the related diseases were based on cumulative physical activity. Therefore, two trips per day was assumed for each MRT users based on the median number of trips made on a weekday in the travel survey. The amount of additional physical activity due to walking to access and egress from the rail system was derived from the travel pattern and people's willingness to walk which was enquired in the survey. A minimum walking duration of 5 min per trip was used to represent those who use motor vehicles to access stations and walk to egress stations. A maximum walking duration of 10 min per trip was used to represent those who walk in both the access and egress trips. The averages of relative risks from both durations were applied in the model. The physical activity assessment were computed to include the whole ridership including induced trips.

2.9. Population of impacts

There were two population of impacts in this study. First, the population of impacts for traffic injuries and physical activity were the entire projected population of MRT ridership (Section 2.2). The population of impacts from the ridership was assumed to be aged 15–74 as they were assumed to make most of the travelling. We also assume that the intention to shift from the motor vehicles to rail transport does not vary between gender and age groups, and applied the general population distribution of Kuala Lumpur and Selangor in year 2015 on the ridership population. Second, the impact from air pollution exposure was modelled on the population catchment of the MRT system. According to the EIA reports of the MRT lines, the first MRT (SBK) and the second MRT (SSP) lines would have 1.2 million and 2.0 million population catchment respectively.

2.10. Sensitivity analysis

Sensitivity analysis evaluated the impact of variable uncertainties in this study (Table A.7). All sensitivity analyses were based on the MRT (SBK). For CO_2 equivalent emissions, the uncertainty analysed were: ridership, induced trip, line haul distance, modal share and access-egress trip distance ratio for motor vehicle. For health burden reduction, additional variables were analysed: walking minutes, background physical activity level, background physical activity using leisure activity only, linear physical activity exposure response relationship, PM2.5 intake fractions and 95% confidence interval (CI) of PM2.5 relative risks. Sensitivity analysis of health impacts from physical activity was done through the analysis of all cause mortality using transport domain activity from NHMS 2006 as the background physical activity (Woodcock et al., 2013).

3. Results

3.1. Travel data and vehicle kilometres travelled

A total of 509 respondents ranging from the ages of 18–79 years were questioned on their conventional weekday travel pattern. Among the respondents, 59% were car drivers and passengers, 18% motorcyclists, 10% rail users, 3% bus users, 4% others and the rest were those with no trips on a particular weekday. A total of 1185 trips on a weekday was recorded from the survey. The median vehicle trip distance was 10.3 km for passenger car and 9.8 km for motorcycle.

Due to the small number of rail users surveyed, the ratio of rail station access-egress distance relative to the origin-destination distance using motor vehicles were combined for passenger car and motorcycle. Overall, the median access-egress distance ratio was 0.42. This means that rail users who used motor vehicle to access or egress stations travelled 58% less kilometres compared to the entire origin-destination journey by motor vehicle. For the access-egress modal share, 48% of rail users used motor vehicles while 24% walked to get to or from the rail stations at the home-end; whereas, only 4% used motor vehicles while 67% walked at the destination-end (Fig. A.1).

Using these inputs, the projected number of vehicle trips and kilometres reduced per day by the modal shift of passenger cars and motorcycles to MRT (SBK) and MRT (SSP) is presented in Table 1. The two MRT lines would reduce 228,000 vehicle trips and 4.2 million vehicle km daily. Passenger cars constituted 54% of the vehicle km reduction which reflected its larger share of modal shift. However, the use of private motor vehicles in the access-egress trips would also produce 324,000 trips and 1.4 million km per day, mostly from passenger cars. This would offset 25% of the total reduction of vehicle kilometres from line haul.

3.2. CO_2 equivalent and PM2.5 emissions

The amount of CO_2 emission reduction is presented in Table 2. The two MRT lines would reduce 242,200 t of CO_2 equivalent per year from private vehicle trips. Motorcycles would contribute 32% of the emission reduction, and passenger cars the rest. Besides, motorised trips in the access-egress of stations would emit another 95,600 t CO_2 equivalents per year which will offset 28% of the

Table 1
Projected number of vehicle trips and kilometres reduced from modal shift per day ('000).

	MRT (SBK)			MRT (SSP)			Total
	PC	MC	Subtotal	PC	MC	Subtotal	
Number of trips							
Line haul	−155	−95	−250	−187	−115	−302	−552
Access-egress	130	17	147	157	21	177	324
Net total	−25	−78	−103	−30	−95	−125	−228
Trip distance (km)							
Line haul	−1596	−935	−2531	−1925	−1127	−3052	−5583
Access-egress	561	70	631	677	84	761	1392
Net total	−1035	−865	−1899	−1248	−1043	−2291	−4190

PC: passenger car, MC: motorcycle

Table 2

CO_2 eq (tons/year) and PM2.5 emissions (g/day).

	MRT(SBK)			MRT (SSP)			Total
	PC	MC	Subtotal	PC	MC	Subtotal	
CO_2 eq (tons/year)							
Line haul	−114,848	−38,306	−153,155	−138,493	−46,193	−184,687	−337,842
Access-egress	40,484	2867	43,353	48,819	3458	52,279	95,632
Net total	−74,364	−35,439	−109,802	−89,674	−42,735	−132,408	−242,210
PM2.5 (g/day)							
Line haul	−20,751	−18,693	−39,444	−25,024	−22,541	−47,565	−87,009
Access-egress	7301	1400	8701	8805	1688	10,493	19,194
Net total	−13,450	−17,293	−30,743	−16,219	−20,853	−37,072	−67,815

PC: passenger car, MC: motorcycle

carbon savings from line haul. For PM2.5 emissions, a total of 67,800 g PM2.5 would be reduced per day. Motorcycle would contribute 56% of the PM2.5 emission reduction while passenger cars would contribute the other 44%. Precursory gases for secondary PM2.5 would also be reduced by 3045 g for SO_2, 1,226, 003 g for NOx and 27,302 g for NH_3 per day.

3.3. PM2.5 concentration

Accounting for the formation of secondary PM2.5 from precursor gases, the ambient PM2.5 concentrations would be reduced by 0.056 $\mu g/m^3$ from MRT (SBK) and 0.068 $\mu g/m^3$ from MRT (SSP). Primary PM2.5 emissions would contribute 91% of the total reduction in ambient PM2.5 concentration. Considering that the baseline PM2.5 concentration in the region was at 28.5 $\mu g/m^3$, the reduction due to the MRT only represents 0.44% reduction from the baseline concentration.

3.4. Health burden

The number of deaths and DALYs that would be prevented from the MRT lines per year are shown in Table 3. For the regional reduction in ambient PM2.5 concentration, the attributable fraction was 0.00050 for acute respiratory diseases (age < 5), 0.00072 for lung cancer and 0.00019 for cardio-respiratory diseases. In total, the two MRT lines would prevent 5 deaths and 104 DALYs annually from air pollution in the population catchment with the highest percentage reduction from lung cancer.

For traffic injuries, the annual reduction in vehicle kilometres travelled would prevent 88 deaths and 6300 DALYs per year. However, the exposure in access-egress trips would offset 45% and 35% of the deaths and DALYs reduction from line haul. Corresponding to the baseline injury statistics (Fig. A.2), the number of motorcycle injuries prevented would be higher than that of passenger cars. Overall, the largest traffic injury benefits would be from the younger age groups (15–34 years) which accounted for more than half (67%) of the DALYs avoided, followed by age group 35–54 (24%) and age group 55–74 (9%). There would be a 0.46 (4%) increase in the number of death for age group 70–74 due to higher rate of pedestrian injuries (Table A.8).

Increased physical activity would reduce 90 deaths and 3200 DALYs annually. The largest reduction would be from cardiovascular diseases, totalling 79 deaths and 2100 DALYs per year. Most (51 deaths) of the prevented deaths would be from ischemic heart disease (IHD) due to its high population incidence (Table A.9). Although no death would be prevented from depression, a large number of disability years would be reduced per year (517 DALYs). Cardiovascular diseases would also contribute the highest percentage reduction of health burden at about 12%, followed by diabetes (11%) and dementia (10%). Population aged 55–74 would

Table 3

Mortality and DALYs avoided by the two MRT lines per year.

	MRT (SBK)		MRT (SSP)		Total	
	Death	DALYs	Death	DALYs	Death	DALYs
Air pollution[a]						
Line haul	−2	−44.2	−4	−88.9	−6	−133.1
Access-egress	0.4	9.7	0.9	19.5	1.3	29.2
Net total	−1.6	−34.5	−3.1	−69.4	−4.7	−103.9
Traffic injuries[b]						
Line haul	−73	−4424	−88	−5335	−161	−9759
Access-egress	33	1568	40	1891	73	3459
Net total	−40	−2856	−48	−3444	−88	−6300
Physical activity[b]	−41	−1443	−49	−1740	−90	−3183
Net total	−83	−4334	−100	−5253	−183	−9587

[a] Population of impacts: MRT (SBK) = 1.2 million; MRT (SSP) = 2.0 million.

[b] Population of impacts: MRT (SBK) = 442,000; MRT (SSP) = 553,000.

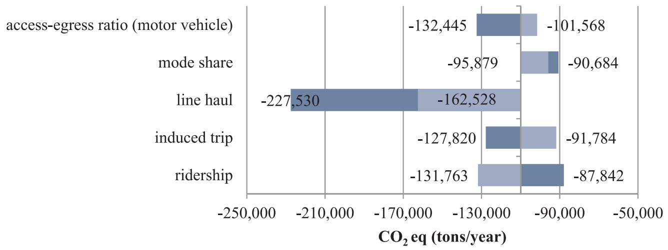

Fig. 3. Sensitivity analysis of CO_2 equivalent emissions.

contribute 57% of the reduction in DALYs, followed by age group 35–54 (31%) and age group 15–34 (12%). The age group 70–74 among males whose background physical activity was slightly higher than age group 65-69 (Table A.10) would result in less benefits due to the curvilinear nature of the exposure response relationship.

In general, the marginal reduction in PM2.5 concentration would contribute small number of health benefits. Traffic injuries and physical activity would bring almost similar number of death reduction while traffic injuries would contribute most of the DALYs reduction. The health benefits from air pollution and physical activity would increase with the age groups, while the prevention of traffic injuries would benefit the young most.

3.5. Sensitivity analysis

Figs. 3 and 4. show the impacts of variable uncertainties on carbon savings and health co-benefits from the MRT system. For carbon savings, the increase in line haul distance would bring significantly more reduction than other variables. Higher motorcycle modal shift would result in less carbon savings but more health benefits from traffic injuries. As our access-egress distance ratio was on the higher end of the reference values (0.2–0.5), the reduction of the distance ratio would increase the carbon savings and health benefits. Using leisure activity only as the background physical activity would only slightly increase the health benefits by 66 DALYs per year. Using linear dose response relationship for physical activity would give a considerably larger benefits than using curvilinear relationship. Sensitivity analysis of impacts from increased physical activity by using all-cause mortality shows a slightly larger benefit (115 vs 90 deaths).

4. Discussion

This study demonstrates that the two MRT lines would reduce 242,200 t of CO_2 equivalents per year based on the changes in private motor vehicle activity. The comparative health impact assessment estimated that 183 deaths and 9,600 DALYs per year would be reduced in the population from the MRT operation. Both physical activity and traffic injuries would contribute similar magnitude of health co-benefits among the MRT users while air pollution would reduce only a small amount of health burden in the population catchment. The use of private motor vehicle in the station access-egress would offset 28% of the carbon savings and 35% of the traffic injuries prevented per year from the MRT system.

In Greater Kuala Lumpur, 6 million trips were made by private transport daily in 2010 (Economic Report, 2011). The vehicle trip distances from the survey were consistent with other local studies at 10 to 15 km (EIA, 2011; Gil Sander et al., 2015). Our results suggest that the overall shift of motor vehicle trips to MRT (SBK) and MRT(SSP) would reduce 2.8% and 3.4% of the CO_2 equivalent annually from private vehicles in the city. Conversely, the operation of MRT (SBK) and MRT (SSP) would produce 98,459 t and 100,776 t CO_2 equivalent per year respectively from electricity generation (EIA, 2011). This gives a net total reduction of 43,000 t CO_2 equivalent per year. Besides, there is a possibility of increased emissions by induced motor vehicle trips due to reduced traffic from modal shift to MRT. Therefore, aside from building more public transport infrastructure, a culture of using public transport need to be developed through education and push factors such as limiting motor vehicle access in areas with public transport connections.

Comparing passenger car to motorcycle emissions, the motorcycle would reduce higher amounts of PM2.5 and NOx given its

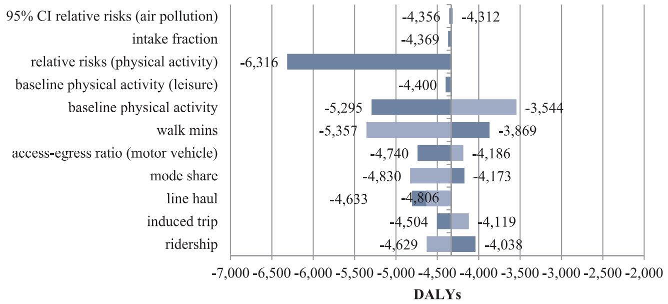

Fig. 4. Sensitivity analysis of health burden.

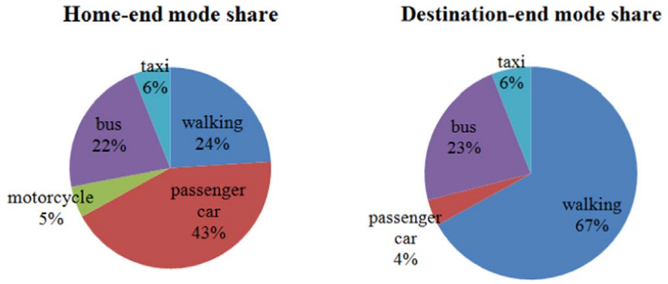

Fig. A.1. Modal share of access-egress at home-end and destination-end of rail users. (Source: Survey on 49 current rail users).

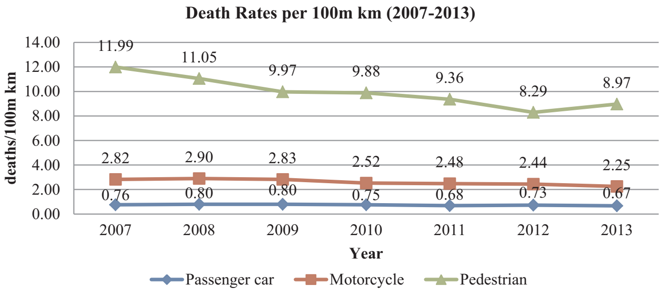

Fig. A.2. Death rates of traffic injury per 100 million km by transport mode from 2007 to 2013 in Malaysia. (Source: Analysis from data by MIROS).

Table A.1
Diseases related to the health determinants in Global Burden of Disease (Maizlish et al., 2011).

Health determinants	Related diseases
Air pollution	
Lung cancer (age > 30)	Lung cancer (trachea, bronchus, lung)
Acute respiratory diseases (age < 5)	Lower respiratory infections Upper respiratory infections
Respiratory diseases (age > 30)	Lower respiratory infections Upper respiratory infections Chronic obstructive pulmonary disorder (COPD) Asthma Other respiratory diseases
Cardiovascular diseases (age > 30)	Hypertensive heart disease Ischemic heart disease Cerebrovascular disease (stroke)
Inflammatory heart diseases (age > 30)	Cardiomyopathy and myocarditis Endocarditis
Physical activity	
	Colorectal cancer Breast cancer Alzheimer and other dementias Diabetes mellitus Depression (unipolar depressive disorders)
Cardiovascular disease	Hypertensive heart disease Ischemic heart disease Cerebrovascular disease (stroke)
Traffic injuries	Road traffic injury (all-cause)

higher emission factors (14 times higher PM2.5 and 7 times higher NOx than car) even though motorcycle was given the lower modal shift percentage. Besides, the conversion from two-stroke engines to four stroke engines for motorcycle causes higher NOx emissions. Therefore, although the motorcycle has lower carbon emission, its detrimental impacts on health from air pollutants should not be neglected. Overall, the use of simple aggregate measure of intake fractions to estimate the effects of emissions on atmospheric PM2.5 concentrations might not have accurately reflected the actual conditions. Although the intake fraction was based on ground level emissions specific to Malaysia, it did not account for the intraurban variability from mobile source PM2.5 (Greco et al., 2007). In addition, the personal exposure during the commute was not assessed. As the two MRT lines cross over at several stations, the population of health impacts might have been double-counted.

For traffic injuries, the number of deaths prevented from motorcycle were 2.5 folds higher than passenger car. These injuries reduction would even be higher should the MRT usage gravitate towards the younger population. While the risks of motor vehicle

Table A.2
Emission factors for greenhouse gases, PM2.5 and other gases (g/km).

	Gases/ air pollutants	Passenger car	Motorcycle	Source
Greenhouse gases	CO_2	193.280	24.82	GEF (2010)
	CH_4	0.109	3.105	NAEI (2013)
	N_2O	0.002	0.002	Griffin (2014)
PM2.5	PM2.5	0.001	0.014	Griffin (2014)
	PM2.5 (tyre wear)	0.005	0.002	Griffin (2014)
	PM2.5 (brake wear)	0.003	0.002	Griffin (2014)
	PM2.5 (road abrasion)	0.004	0.002	Griffin (2014)
PM2.5 precursor	NOx	0.080	0.540	GEF (2010)
	SO_2	0.001	0.0004	Griffin (2014)
	NH_3	0.010	0.002	Griffin (2014)

Table A.3
Emission factors for cold start (g/trip) and global warming potential.

Gases/ air pollutants	Cold start (Passenger car) (Griffin 2014)	Global warming potential (IPCC 2013)
NH_3	0.012	
NOx	0.243	
N_2O	0.010	265
CH_4		28
CO_2		1

Table A.4
PM2.5 Intake fractions.

Primary emissions	Precursors	Intake fraction (ppm)	Scaled intake fraction	Breathing rate ($m^3 person^{-1} day^{-1}$)	References
Primary PM2.5	–	24.00		14.5	Apte et al. 2012
Secondary PM2.5	SO_2	0.99	0.54	13.0	Humbert et al. 2011
	NOx	0.20	0.11	13.0	
	NH_3	1.70	0.93	13.0	

Table A.5
Relative risk functions for PM2.5 air pollution (Ostro, 2004).

Outcome	RR function	β
Cardio-respiratory (> 30)	exp[β(X-Xo)]	0.00893
Lung cancer (> 30)	exp[β(X-Xo)]	0.01267
Acute respiratory infections (< 5)	exp[β(X-Xo)]	0.00332

X = baseline PM2.5 concentration (μg/m^3).
Xo = counterfactual concentration of PM2.5 (μg/m^3).

Table A.6
Relative risk parameters for physical activity related diseases (Woodcock et al., 2014).

Diseases	MET h/ week	Relative risk	Power (t)
Breast cancer	3.5	0.94	0.50
Colon cancer (Male)	31	0.80	0.50
Colon cancer (Female)	30	0.86	0.50
Cardiovascular disease	5.4	0.84	0.50
Dementia	24.5	0.72	0.50
Depression	0.8	0.96	0.50
Diabetes	5.6	0.83	0.375
All cause mortality	11	0.89	0.375

injuries fell with age, pedestrian injury rates increased among the older population probably due to falls (Avineri et al., 2012; Tournier et al., 2016; Gyllencreutz et al., 2015). The changes in risks for other road users such as reduced risk of vehicle collisions and increased vehicle speed due to less traffic were not modelled. However, measures such as speed limits is necessary to prevent accidents from reduced traffic (Kloeden et al., 1997; Moore et al., 1995). In addition, Manan and Várhelyi (2012) stated that

Table A.7
Range of figures for variables in sensitivity analysis.

	Dark shading	Center	Light shading
Ridership	−20%	MRT(SBK): 442,000 MRT(SSP): 553,000	+20%
Induced trips	5%	15%	25%
Line haul (km)	21 km (75th percentile of private vehicle trip distance)	car: 10.3 km motorcycle: 9.8 km	15 km (rail journey distance including transfer)
Mode share	60%car, 30%motorcycle, 10%bus	66%car, 33%motorcycle, 1%bus	33%car, 66%motorcycle, 1%bus
Access-egress ratio (motor vehicle)	0.20	0.42	0.50
Walking minutes/day	8	10	33
Baseline physical activity	5th percentile	mean	95th percentile
Baseline physical activity (leisure)	leisure background	mean	–
Relative risk (physical activity)	linear	curvilinear	–
Intake fraction	PM2.5 = 44 SO_2 = 0.99 NOx = 0.20 NH_3 = 1.70 (Humbert et al. 2011)	PM2.5 = 24 SO_2 = 0.59 NOx = 0.11 NH_3 = 0.93	–
Relative risk (air pollution)	95% upper CI	relative risks	95% lower CI

Table A.8
Relative risks of traffic injuries for shifting from motor vehicle to MRT.

Age	Death	Major injury
15–19	0.19	0.22
20–24	0.27	0.24
25–29	0.32	0.25
30–34	0.37	0.31
35–39	0.40	0.35
40–44	0.38	0.31
45–49	0.39	0.34
50–54	0.40	0.32
55–59	0.53	0.40
60–64	0.69	0.53
65–69	0.64	0.49
70–74	1.04	0.87

Table A.9
Attributable mortality and morbidity of increased physical activity by related diseases from MRT use.

	MRT (SBK)		MRT (SSP)		Total	
	Death	DALYs	Death	DALYs	Death	DALYs
Breast cancer	−1	−22	−1	−27	−1	−49
Colon cancer	−1	−21	−1	−25	−2	−46
Dementia	0	−8	0	−10	0	−18
Depression	0	−234	0	−283	0	−517
Diabetes	−4	−178	−5	−214	−8	−392
Hypertensive heart disease	−1	−39	−2	−47	−3	−85
Ischemic heart disease	−23	−627	−28	−756	−51	−1,382
Cerebrovascular heart disease	−11	−314	−14	−379	−25	−693
Total	−41	−1,443	−49	−1,740	−90	−3,183

underreporting of severe injuries was up to 600% and slight injuries up to 1400% in Malaysia. A comparison of 2008 data from MIROS with that from the Ministry of Health indicated the same number of deaths were recorded but there was an underreporting of traffic injury incidence by 4.6 folds. Therefore the attributable fractions were applied to the GBD 2013 data in this study, which already allowed for underreporting.

For rail users, the station access and egress are the most direct opportunity to incorporate physical activities through walking. These walking activities could be important amongst the most sedentary population groups that constitute the majority of the urban population today (Samitz et al., 2011; Kelly et al., 2014). Sensitivity analysis of physical activity through all cause mortality shows that there could be more health benefits such as social interaction other than those diseases included in this study (Boniface et al.,

Table A.10
Background physical activity level (work & leisure) in METs-hour per week. (Source: Analysis from data in NHMS 2006).

Age	Male	Female
15–19	6.97	5.54
20–24	11.66	6.08
25–29	13.12	7.95
30–34	12.42	8.03
35–39	11.91	7.77
40–44	11.18	7.84
45–49	11.81	7.38
50–54	10.54	7.94
55–59	9.07	4.30
60–64	5.27	4.36
65–69	2.44	2.45
70–74	2.74	0.89

2015). Besides, the background physical activity level did not include household activity domain, which might have overestimated benefits especially among females.

Sensitivity analysis on variables identified line haul distance as the main determinant of the carbon emissions model. Rail transport journeys (15 km) were on average longer than private vehicle trips (10 km) in the travel survey, which is similar to other studies (Goel and Tiwari, 2015; Vijayakumar et al., 2011). Thus, the estimates in the main analysis using private vehicle trip distance was conservative. Using leisure activity as the background physical activity resulted in small changes although most of the relative risks used in the model were based on leisure activity domain.

The results in this study were consistent with previous studies although those studies did not specifically include the access-egress modes. The replacement of 20% car trips with public transport in the Barcelona metropolitan could reduce 20 deaths per year in a population of 1.6 million (Rojas-Rueda et al. 2012). In Adelaide, the replacement of 20% of passenger vehicle kilometres travelled (6.7 million VKT) would reduce 122 deaths and 1,892 DALYs in the population year of 2030 (Xia et al. 2015). Although the study by Rojas-Rueda et al. (2012, 2013) on personal air pollution exposure by public transport mode found slight increase in mortality, the benefits from physical activity have been shown to outweigh the risk of exposure to the level of air pollution for walking (Tainio et al., 2016). These results indicated that shifting from private vehicles to public transport could on overall bring health benefits.

The modal shares of passenger cars in the access and egress trips obtained in the survey reflected that of car-dependent United States which lay between 27.0% and 51.6% by park-and-ride (Bergman et al., 2011; Vijayakumar, 2011; Semler and Hale, 2010; Khalid et al., 2014). Besides, the tendency to use private mode at the home-end stations has facilitated the availability of park and ride facility at 16 out of 31 stations of MRT (SBK) and 15 out of 37 stations of MRT (SSP) in order to encourage ridership. However, the access-egress distance ratio which usually lies between 0.2 to 0.5 (Krygsman et al., 2004; Goel and Tiwari, 2015) might be overestimated due to lack of rail services in the study area. Nonetheless, the implementation of public transport friendly policies in the city centre might have encouraged people to use it despite the longer access-egress distance. With the development of the MRT, the access-egress ratio may fall over time as more settlements are built close to the infrastructure (Durand et al., 2016).

All the input data in the model were obtained from the travel survey and local sources where available. However, the insufficient information on rail transit use was one of the major limitations in this study because of the small sample of rail users from the survey due to the dominance of private motor vehicle modal share in the population. The sample size in this study might also have not sufficiently captured the characteristics of travel choices in the area. For verification of the results from this study, the travel characteristics of the MRT users before and after using the MRT system could be collected when sufficient ridership has been achieved.

5. Policy implications

The government's policy to focus on the development of integrated public transport system through the establishment of the MRT system would contribute to the national target of reducing carbon emissions while introducing health co-benefits among the locals. This study shows that the choice of transport mode in the station access-egress is important to get the greatest emissions reduction and health co-benefits in the long term. Despite the overall reduction in the use of private transport mode, it seems that the vehicles on the roads in the direction towards the stations in the area would not reduce much, if not increase, due to motor vehicles accessing the stations. Thus it is essential that safe and direct walking routes are provided for pedestrians to access the stations. This is to ensure their safety and realise the potential health benefits especially protection from traffic injury risk which would be much more immediate compared to the chronic diseases reduction.

In addition to building rail infrastructure, bus services and cycling should be encouraged to replace private motorised trips in the access especially at the home-end stations. Bus rapid transit (BRT) that connects MRT stations to residences and workplaces would avoid the daily traffic gridlock and attract more people to use buses instead of driving to the stations. Currently cycling is not a common mode in Greater Kuala Lumpur but it has the potential to enable access to the station from a much wider catchment area than walking and is far more space efficient than driving. Providing infrastructures for cycling such as protected cycling lanes and bicycle parking facilities could be a way to encourage alternative transport and further improve the health co-benefits of metro development. Reducing the number of motor vehicles accessing the stations would also improve pedestrian safety.

6. Conclusion

This study demonstrated that the two forthcoming MRT lines in Greater Kuala Lumpur could reduce carbon emissions from private transport and improve urban population health. The prevention of traffic injuries and increased physical activity among the user population would accrue equally important health co-benefits, followed by smaller co-benefit from the reduction in air pollution in the population catchment area. However, this study also underscored the role of the access and egress of the MRT stations in carbon emissions and health co-benefits overall. Therefore, careful planning around the MRT stations is necessary to realize the amount of benefits brought by the MRT system. This is the first study in Malaysia that quantitatively relates multiple health impacts to public transport infrastructure. The results from this study could inform future planning of rail transport in expanding cities, especially of the developing countries.

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Appendix A

See Figs. A.1 and A.2.
See Tables A.1–A.10.

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