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Evaluating the mobility and environmental effects of light-rail transit developments using a multi-state supernetwork approach

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ABSTRACT

Mass light-rail transit (LRT) has been promoted as an effective solution toward sustainable transportation in urban areas. This paper presents a micro-simulation framework combining the multi-state supernetwork (MSN) approach and a mobility-related emission module to evaluate the mobility and environmental effects of LRT developments. The evaluation framework considers individuals' mode choice of LRT and particularly the trip chaining with their private vehicles to conduct daily activity programs. As complementary policies to LRT developments, parking pricing and park & ride (P + R) developments are also integrated. The output of daily travel patterns from the MSN approach can be used congruently to calculate the air pollutant emissions. The framework is applied to the extended Metropolitan area of Eindhoven (the Netherlands), where new LRT developments and additional parking policies are considered to improve accessibility and reduce environmental effects. The micro-simulation concerns a synthetic population of approximately 110,000 individuals and seven LRT scenarios. The simulation results show a decrease in overall vehicle kilometers traveled and travel time, an increase in public transport use, a decrease in total air pollutant emissions, and an increase in activities in areas around public transport stops and P + R locations. It appears that the inclusion of parking measures in the simulations strengthens the effects, confirming the effectiveness of policy combinations.

1. Introduction

The continuous growth of cities across the globe often coincides with an increase in road congestion and pollution and a decrease in accessibility and livability caused by motorized vehicles. To reduce the problems regarding congestion and livability, urban and transport planners have explored several solutions that decrease the amount and use of motorized vehicles (Rye & Hrelja, 2020). One of these solutions concerns the introduction of light-rail transit (LRT) to mitigate car traffic congestion on certain corridors (Van der Bijl et al., 2018). In their overview of various LRT projects worldwide, they identified five essential domains in the argumentation for LRT, namely, effective mobility (effectiveness of transport and mobility), efficient city (suitability of spatial use and urban development), economy (prosperity and wellbeing in/for cities), environment (decrease carbon footprints; sustainable cities), and equity (social inclusive cities). Especially with respect to the environment, they see advantages when the LRT is lowering traffic volumes and vehicle movements resulting in higher accessibility and higher livability of areas. This is in line with the findings of Wiersma et al. (2017) who concluded that providing fast and direct public transport connections has an effect on reducing car–dependency within regions. More specifically, Spears et al. (2017) found a reduction in driving of approximately 10 miles per day due to a new LRT line in Los Angeles (USA). Based on another study regarding the same LRT development, Boarnet et al. (2017) found that households residing within a half-mile from an LRT station produce 27 percent less CO_2 emission with their motor vehicles.

To evaluate land-use transport scenarios, such as LRT developments, and to provide decision-makers with detailed information regarding impacts on residents' travel behavior, activity-based modeling of travel demand has gained momentum in the academic field over the past decades (Rasouli & Timmermans, 2014). It is considered as an advanced alternative compared to the classic four-step trip-based models, which have more debatable limitations but are still a dominant method in practice for policy-making. Based on several criticisms, there are increasing reasons for replacing an aggregate spatial interaction model

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like the four-step trip-based model with a disaggregate travel demand model of higher behavioral realism. The activity-based models conceptualize travel as the derived demand of activity participation at the destinations and emphasize trip chaining at a high spatial and temporal resolution. Therefore, these models are better suited to model the interdependencies between different aspects underlying a daily activity-travel pattern and consequently sensitive to a broader set of land-use transport policies and developments. Various developments of activity-based approaches have been explored and included in a number of micro-simulation systems such as Albatross (Arentze & Timmermans, 2000), Feathers (Janssens et al., 2007), and MATSim (Horni et al., 2016). Yet, only a limited number of studies connect these micro-simulation systems to emissions (e.g. Shiftan & Suhrbier, 2002; Beckx et al., 2009; Hao et al., 2010; Hatzopoulou & Miller, 2010).

One of the network-based approaches regarding activity-based modeling of travel demand concerns the so-called multi-state supernetwork (MSN) (Arentze & Timmermans, 2004), which captures individual multi-modal multi-activity patterns at a high level of behavioral detail. The MSN provides a representation of the action space of conducting an activity program and simultaneously models the choice of activity location, travel mode, route, and activity sequence. In recent MSN formulations (Liao et al., 2011, 2013; Liao, 2016), the individual activity-travel scheduling model is capable of addressing large scale dynamic multi-modal transport networks with the consideration of chained effects of time window constraints, waiting and transfer in the public transport system, parking location choice, and activity duration choice that do not appear in other peer scheduling models. Given the outcomes of detailed activity-travel patterns, the potential of the individual activity-travel scheduling model in a micro-simulation system demonstrates to have the added value to predict changes in travel choice decisions responding to the adaptions over an integrated land-use transport system (Liao et al., 2017). However, the micro-simulation system has been thus far not applied for real-world policy assessment of emissions.

Based on their research, De Bruijn and Veeneman (2009) concluded that the introduction of LRT is often accompanied by many uncertainties that delay the process of introduction. In view of this finding, the current study aims to extend the MSN-based micro-simulation system to get better insight into the effects of a newly developed LRT system on both individuals' travel patterns and system-level air pollutant emissions. The system extension involves the coupling with an emission module to derive the air pollutant emissions, provided by the European Commission with the Mobility and Transport themes. This index provides insights into the amount of air pollutants received by residents that might cause serious illnesses and are considered harmful to physical health. Besides the effect of the separate parts of the LRT system, attention is paid to the effects of a supporting parking pricing policy. Implementing a parking pricing policy is considered as a complementary option for synchronizing policies in the land-use transport system (Van Wee et al., 2014). Therefore, an additional dimension of the policy scenarios evaluates the effects of parking price adjustments and park and ride (P + R) facilities together with the LRT development. Concerning the societal relevance, advanced activity-based transport modeling with a more efficient policy assessment is expected to obtain promising mobility and environmental indicators to support transport policy-making. To that end, the current study focuses on the evaluation of a number of policy scenarios centered at the LRT development considering the metropolitan area of Eindhoven (*MRE* + 8, Netherlands) as a study area.

The remainder of this paper is organized as follows. Section 2 presents the MSN-based evaluation framework. Section 3 introduces the study area, data sources, parameter settings, and the scenarios of the LRT development. In the fourth section, the results of the simulation and policy implications are presented. The paper ends with conclusions of the research and suggestions for transport practitioners.

2. Evaluation framework

In this section, we first introduce the MSN-based individual activity-travel scheduling model, which underlies the core of the evaluation framework. It should be noted that even though the scheduling model has been well discussed in the field of transport network modeling (Liao et al., 2013, Liao, 2016), it is relatively new to transport policy-making and thus we summarize the quintessence. Next, the coupling with an emission module is discussed. In what follows, we present the framework for evaluating the mobility and environmental effects.

2.1. Msn-based activity-travel scheduling

The concept of multi-state supernetwork (MSN) (Arentze & Timmermans, 2004) was originated to consistently represent multi-dimensional activity-travel patterns imitating path choice in augmented networks (Nagurney, 2004). As the original MSN representation suffered from combinatorial explosion and was not operationalized, Liao and coworkers suggested an improved representation and the concept of personalized networks to reduce the supernetwork scale and developed efficient routing algorithms (Liao et al., 2010, 2011, 2012, 2013, 2014, 2017). In general, the MSN representation encompasses the choice of multi-modal, multi-activity trip chains, and even locations of facilities or services, reflected by the choice of daily activity-travel patterns of individuals with respect to an individual's activity programs. Below is a list of key terminologies of MSN.

- *Daily activity program: The list of out-of-home activities during the day, available private vehicles, and (in-)complete sequence between activities;*
- *Activity state: The condition of which activities in a daily activity program have already been conducted;*
- *Vehicle state: The location of the private vehicles (in use or parked at particular locations);*
- *Activity-vehicle state: The combination of activity and vehicle states. If an individual is conducting* an activity, the private vehicles must be parked.

A MSN representation is constructed for each individual in two main steps. First, a copy of private vehicle network (PVN) or public transport network (PTN) is created for every possible activity-vehicle state. Second, PVNs and PTNs are interconnected by transition links (between PVNs and PTNs), denoting the change of vehicle states, and transaction links (between PTNs and PTNs), denoting the change of activity states. Fig. 1 shows a representation of conducting two activities A_1 and A_2 with two available private vehicles (i.e. car and bike). The parking locations are for cars (P_1 and P_2) and bicycles (P_3 and P_4), respectively. The hexagons and pentagons denote PTNs and PVNs respectively, and the vertices denote locations (home – H, parking locations – $P_{1\text{-}4}$, and activity locations – $A_{1\text{-}2}$); P_0 and P_5 denote the vehicle states that car and bike are in use respectively, and s_1s_2 denotes the activity states of A_1 and A_2 (0: not conducted; 1: conducted). All home-based trip chains start from H^0 in the first row and end at H^1 in the last row, and the undirected links are bi-directed. The path indicated by the bold links in Fig. 1 represents an activity-travel pattern that this individual departs from home by car with parking at P_2 and travels through PTN to conduct A_1. Then, the individual picks up the car and returns home to switch to bike with parking at P_4 and goes through PTN to conduct activity A_2, and finally returns home with all private vehicles parked and all activities conducted.

In the MSN representation, the attributes on each link are dependent on travel mode and activity state. Considering time-dependencies in travel time, parking search time, and activity duration, the disutility (or generalized link cost) of each link of the MSN can be defined as

$$disU_{isml}(t) = \beta_{ism} \times X_{isml}(t) + \epsilon_{isml} \tag{1}$$

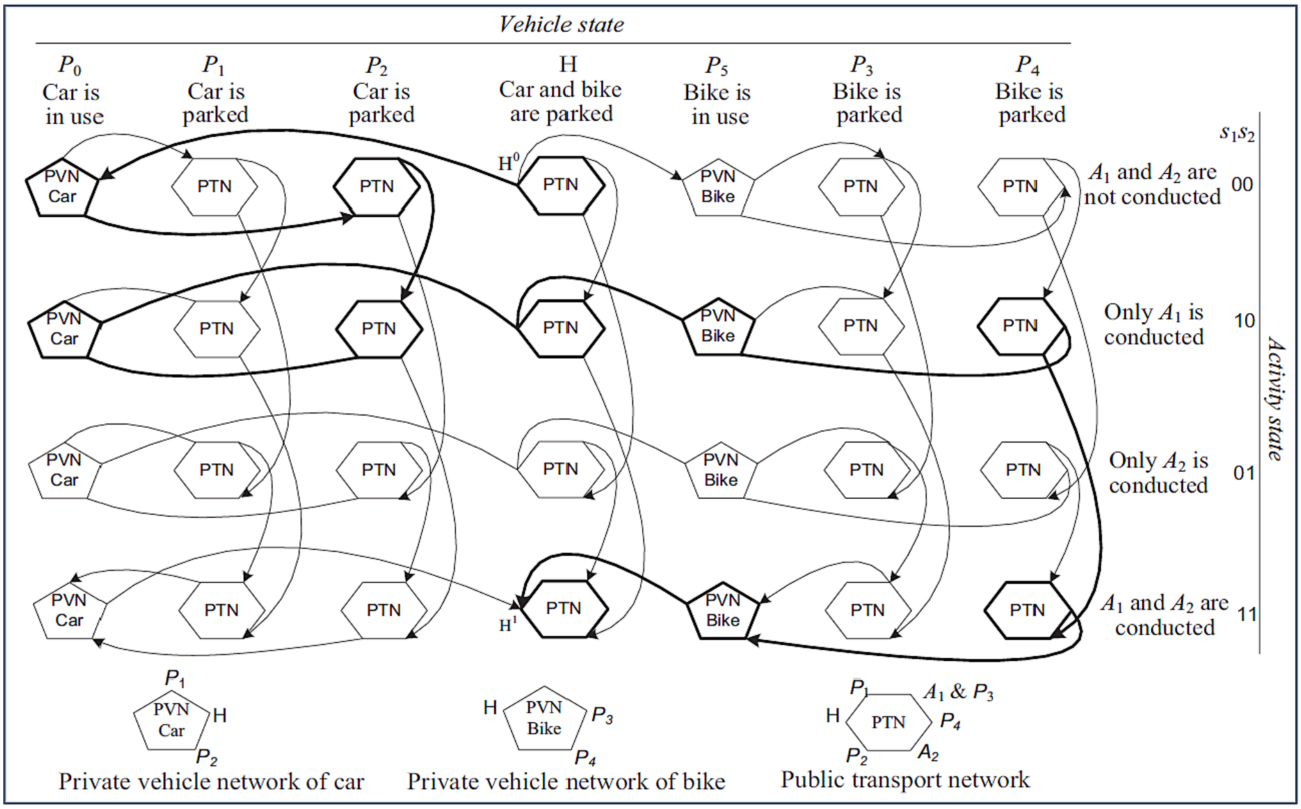


Fig. 1. Example of multi-state supernetwork representation (Liao, 2016).

where $disU_{isml}(t)$ denotes the disutility or the costs on link l for individual i at activity state s and with mode m; $X_{isml}(t)$ denotes the vector of attributes where a time-dependent component is added with t as the arrival time on link i; β_{ism} denotes the attribute-vector of factor weights representing the individual preference which remains stable through time; and ε_{isml} denotes the error term.

To make the scheduling model tractable, personalized PVNs and PTNs are constructed for each individual's activity program. As illustrated in Fig. 1, the scale of the MSN depends on the number of vehicle states given a fixed number of activity states. A location choice model is applied to reduce the number of activity locations for flexible activities and indirectly the number of parking locations, i.e., vehicle states. The disutility function for selecting activity locations is specified as

$$disU_{fn} = \alpha_{fn} + \beta_{iAD} \times \ln\left(1 + aDist_{fn}\right) - \beta_{iS} \times bAttr_{fn} \tag{2}$$

where $disU_{fn}$ is the choice-related disutility of conducting flexible activity f at location n, α_{fn} is the base disutility, $aDist_{fn}$ is the travel distance from the previous fixed activity location to n, $bAttr_{fn}$ is the attractiveness of fn, and β_{iAD} and β_{iBA} are disutility coefficients for travel distance and attractiveness respectively. Since Eq. (2) can well balance the positive and negative factors of activity locations, the MSN only loses little accuracy by selecting a small number of activity locations for flexible activities in representing the action space. The coefficients in Eqs. (1–2) are heterogeneous and thus should be estimated based on personal characteristics.

After all the link disutilities are defined, the individual activity-travel scheduling is performed based on a path-finding algorithm according to the principle of disutility minimization. The individual activity-travel scheduling predicts where, when, with which transport modes and following which routes to conduct the activities. Due to the flexibility of the MSN, the seminal representation can further be extended to incorporate new modalities such as private electric bikes, shared cars and bikes, and virtual mobility (e.g. teleworking and teleshopping). These mobility-related indicators relate to the ease with which individuals can conduct daily activities, i.e., accessibility (Liao et al.., 2017).

2.2. Coupling with an emission module

As explained above, the individual activity-travel scheduling model intends to reproduce the individual detailed daily activity-travel patterns in space and time. Although individuals may not take into account emissions for making activity-travel decisions, the detailed patterns allow us to trace the emission footprint associated with mobility in different modalities. Hence, the scheduling outcomes at a collective level can be naturally coupled with an emission module to calculate the emissions. According to the European Union vision of mobility and transport, promoting sustainable urban mobility and increasing the usage of cleaner and energy-efficient vehicles is the main objective to provide a better quality of life for citizens (European Commission, 2020a). The aggregated emission amount regarding the air pollutants of Nitric Oxide (NOx) and fine Particular Matter (PM2.5) are calculated according to the total passenger vehicle traveled distance (Vkm), the characteristics of vehicle fuel type, and emission standard level. These emitted air pollutants are the input of an air pollutant emissions indicator namely “Emission Harm equivalent Index (EHI)” provided by the transport department of the European Commission. The indicator is expressed in terms of emission harm effect on health using PM2.5 equivalents, based on the commission's methodology developed in the context of the “Clean Air Program” in “National Emissions Ceilings Directive discussions” (European Commission, 2020b). The indicator formula (Eq. (3) and the essential parameters (Table 1) are described as

$$EHI = \frac{1000^{*}\sum_{ij}\sum_{k}\sum_{c}\sum_{s}A_{ij}{}^{*}S_{ijk}{}^{*}C_{ijkc}{}^{*}E_{ijkcs}{}^{*}Eq_{s}}{cap} \tag{3}$$

Bringing together MSN and the mobility-related emission module gives transport policy decision-makers a more complete picture of the envi-

Table 1
Notation of the EHI index components.

EHI = Emission harm equivalent index [kg PM2.5 eq./cap per year]
i = Vehicle type transport mode (passenger car, tram, bus, train, motorcycle, inland vessel, freight train, truck, etc.) [type]
j = Vehicle class (if available specified by the model (e.g., SUV, etc.)) [type]
k = Energy type (petrol, diesel, bio-fuel, electricity, hydrogen, etc.) [type]
c = Emission class (European standard) [type]
s = Type of substance limited to NOx and PM2.5 (exhaust and non-exhaust) [type]
A_{ij} = Activity volume (distance driven by transport mode i and vehicle type j) [million Vkm per year]
S_{ijk} = Share of fuel type k of transport mode i and vehicle type j [fraction]
C_{ijkc} = Share of emission class c of transport mode i, vehicle type j, and fuel type k [fraction]
E_{ijkcs} = Emission of pollutants per Vkm driven by transport mode i, vehicle type j, fuel type k, emission class c, and type of substance s (g/km)
Eq_s = Emission PM2.5 equivalent health impact value for substance type s [factor]
cap = Capita or number of inhabitants in the urban area [#]
(Multiplication by 1000 for unit transformation)

ronmental consequences of new LRT developments. MSN shows the effects with regards to travel patterns as a reflection on the use of infrastructure based on the lowest disutility assignment of a route, while air pollutant emissions show the environmental consequences in terms of emissions.

2.3. Msn-based micro-simulation

To evaluate the LRT developments, in combination with the MSN-based activity-travel scheduling model and the emission module are integrated into a micro-simulation system (Fig. 2). The micro-simulation includes the following parts:

1. generate the synthetic population with activity programs in a study area;
2. define policy scenarios in the integrated land-use transport system;
3. specify individual activity-travel preferences;
4. simulate individual activity-travel patterns;
5. aggregate output of activity-travel patterns at the population level;
6. determine the aggregate emission levels.

The main part of the adopted evaluation framework concerns the "MSN micro-simulation system" in the middle of Fig. 2. Based on the activity programs of the synthetic population and imported parameter settings, the PTN and PVNs (one PVN per private vehicle) of each individual are generated from the multi-modal transport network (see Liao et al., 2011; 2013; for detailed explanations). After all the PTN and PVNs are prepared, a personalized MSN is constructed according to the main steps as introduced in Section 2.1. Afterward, for each individual, the optimal path in the MSN is found as the predicted daily activity-travel pattern. At the collective level, all the predicted activity-travel patterns are aggregated and standardized to match the input to the emission module for determining the effects on mobility and emissions. It should be noted that aggregation in Fig. 2 does not take into account the feedback of possible aggregate traffic on the input of dynamic network travel times. This treatment is acceptable with the aim of evaluating the potential direct effects on travel patterns adaptation before the LRT system is introduced.

The newly added LRT lines are arranged as a series of basic connections tagged with a 5-tuple $<stop_{st}, stop_{end}, time_{st}, time_{end}, line\ number>$ describing the start and end stops, start and end times, and line number. These basic connections are transformed into a realistic time-expanded network according to Pyrga et al.. (2008) and added to PTNs in the multi-state supernetwork. Given the time that a car is parked to the time a traveler picks up the car, there are many possibilities of duration through the PTNs. The produced disutility because of car parking cost differs considerably from the chosen routes and activity locations while the car is parked. Hence, the produced disutility should also be duration-dependent. Fig. 3 is an extract from Fig. 1 and exemplifies a chain of parking process, in which P_1 and P_2 denote two parking locations (either for P + R or activity locations), $R_1\&R_2$ and $R_3\&R_4$ represent examples of alternative routes going through PVNs and transaction links. R_2 and R_3 are two highlighted routes associated with parking location choice of P_1 and P_2 respectively. The parking durations equal to the time spent on these routes. In the micro-simulation, we adopted a linearized parking pricing profile for a parking location, which is structured as:

$$y_{P_k} = a_{P_k} + b_{P_k} \times t \tag{4}$$

where y_{P_k} (€) and t (hour) denote monetary cost and parking duration at parking location P_k respectively.

3. Light rail Eindhoven

3.1. Study area

Recently, the municipalities in the Eindhoven region draw attention to the accessibility of several urban economic core areas in the region (Gemeente Eindhoven, 2019). The main issue is that the current public transport network connections are less suitable to serve the local activity

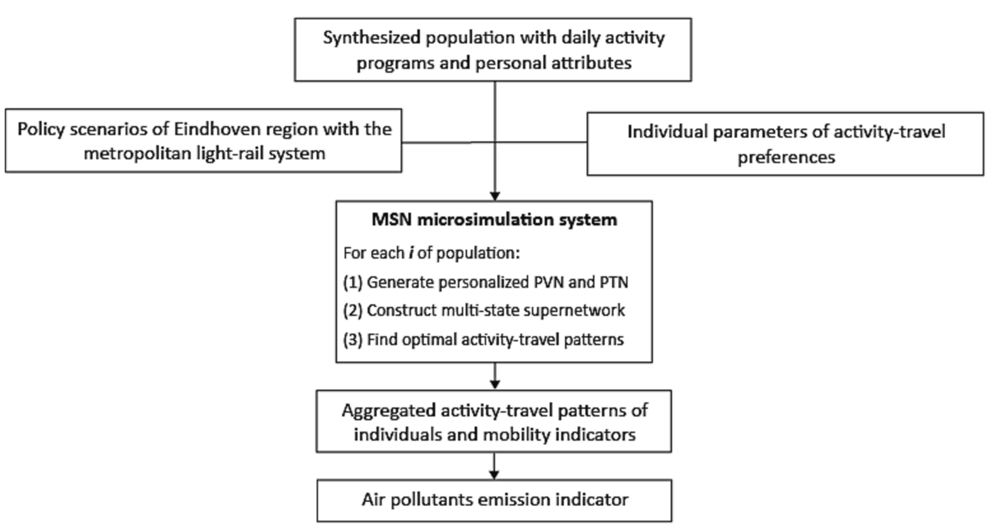


Fig. 2. Flow chart of MSN-based micro-simulation.

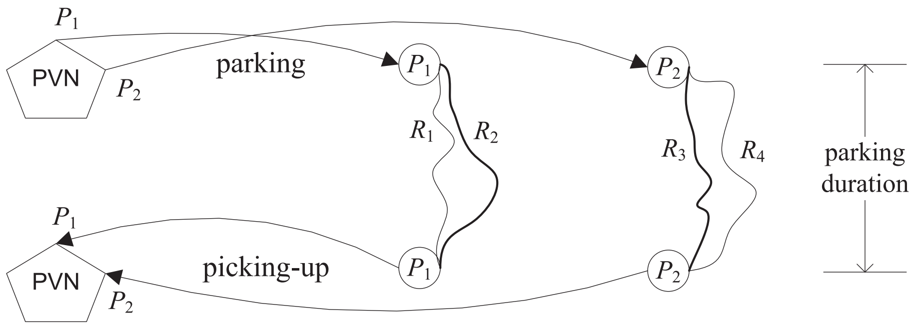


Fig. 3. Car parking duration in multi-state supernetwork.

hotspots in the region such as the Eindhoven city center, Eindhoven Airport, ASML industrial hub, and High-Tech Campus. Also, the regional high occupancy vehicle (HOV) or bus capacity under the current settings is incapable of serving the dramatic growing commuting demand for regional travelers. Mobility professionals argued that the public transport system should bring travelers closer to their destination, while there is little effect on travelers' accessibility if the public transport authorities remain to invest in the current rail network (Van Gompel, 2019). However, the accessibility problem of the Eindhoven region has been discussed primarily at the urban level instead of a regional scope to date. Therefore, urban transportation professionals have been discussing various alternatives to deal with regional capacity and accessibility issues including introducing the new metropolitan public transport concept (Vermeeren, 2020). This concept mainly suggested introducing a "Metropolitan Light-Rail system" that could replace the current regional access infrastructure of high-quality public transport (HOV) and stop-train system (Sprinter). The proposed Metropolitan LRT system introduces three potential LRT lines (A, B, and C) covering an additional 81 km connection overall. The suggested lines are presented in Fig. 4 and connect the center of Eindhoven with various locations in the region.

A further detailing of the three LRT lines is based on the conceptual plan "Light-rail in Brainport Eindhoven" presented by Donners and Hannema (2019). LRT Line A connects three major municipalities in the province of North-Brabant: Tilburg, Eindhoven, and Helmond. The service area includes various regional hotspots such as Eindhoven

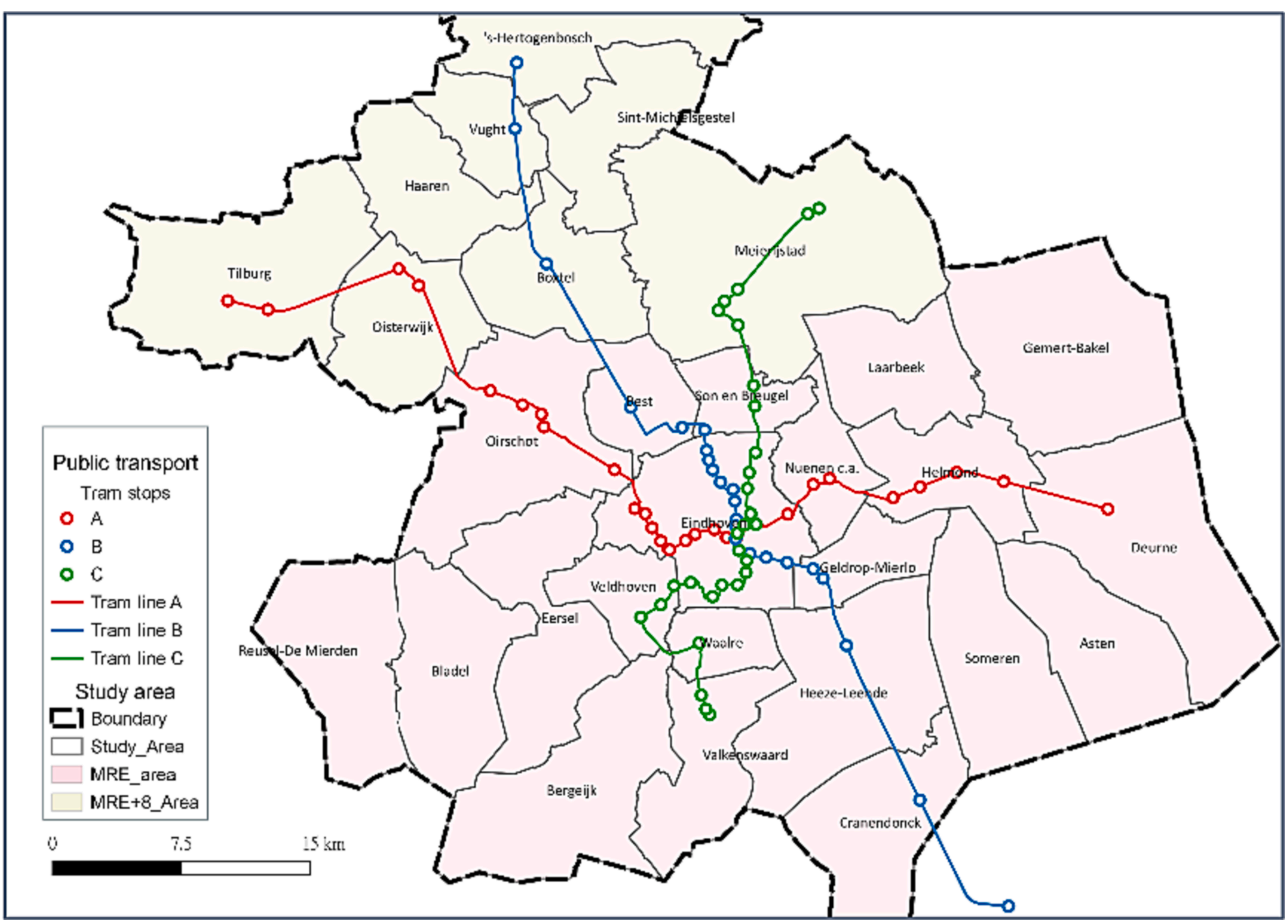


Fig. 4. Eindhoven Light-Rail ambition and MRE + 8 study area (revised from Donners & Hannema, 2019).

Airport, urban development Strijp-S, Eindhoven University of Technology, Tilburg University, and the Automotive Campus in Helmond. In total, there are 30 stops and 7,424 connections per day planned for LRT Line A. The line is partially combined with rail infrastructure of the Dutch Railways and covers a total length of approximately 65 km. The total travel time of the full LRT Line A connection is approximately 70 min. LRT Line B connects two major municipalities in the province of North-Brabant: 's-Hertogenbosch and Eindhoven. The connection further reaches various neighborhoods in the district Woensel, the industrial area Ekkersrijt, DAF truck industrial agglomeration, and terminates at the municipality of Weert in the province of Limburg. In total, there are 25 stops and 4,944 connections per day for LRT Line B. Also, this line is partially combined with the rail infrastructure of the Dutch Railways and serves a distance of approximately 64 km and a total travel time approximately 65 min. Finally, LRT line C connects the regions in the surrounding of Eindhoven including the municipalities of Meierijstad, Veldhoven, and Valkenswaard. The connection also serves various regional hotspots such as the ASML campus in Veldhoven, High-tech Campus, and Eindhoven University of Technology. In total, there are 30 stops and 7,424 connections per day for LRT Line C. The total length of this light-rail line is approximately 46 km. The total travel time with a full duration of line C connection is approximately 60 min.

3.2. Data sources

The following information is needed to carry out the simulations using the MSN approach. For an individual's daily activity program of the *synthetic population*, the Dutch annual mobility survey MON/OViN (CBS/RWS, 2005-2009; CBS/RWS, 2010-2017) databases have been extracted from the years 2005 to 2017 in a total of 13-year resources to obtain a sufficient sample size for model input. Individuals of 12 years old or older having at least one out-of-home trip (start from home) on the observed day of the activity-travel diary surveys are selected, resulting in approximately 110,000 persons (approximately 8 percent of the total population) and 307,000 trips. To match with the population of the region, the sample is adjusted according to sampling weights embedded in the surveys. The *land-use* raw datasets *for activity locations* utilize BAG (Basic Registration of Buildings of the Cadaster) within the study area as the file input (Esri Nederland, 2020a). The input data concerns the available facilities and services for individuals to participate in the daily activity programs as appeared in the daily travel diaries, including work, education, shopping, going-out for social visits, or recreational tour. Amongst these, work and education are fixed activities with known activity locations, while others have flexible activity locations. The data is used in combination with the 4-digit (PC4) and the 6-digit level (PC6) of postcode data extracted from the ESRI Nederland database (Esri Nederland, 2020b). The raw datasets regarding the *road network* are extracted from the internal Aimsun Next software (Version 8.4) database provided by mobility professionals (Consultancy Royal-Haskoning/DHV). The road network including the sections (edges) and junctions (nodes) shapefiles are exported from Aimsun software and imported into QGIS software for data format modification. Different road categories with corresponding maximum speed for cars and bicycles, and cars' fuel consumption are considered. The *public transport timetable data* is fully extracted from the Dutch open data "OVapi GTFS" provided by the OpenMobilityData portal (2020). This open public transportation database is available with daily updated information covering all routes and transit stops in the Netherlands.

3.3. Parameter settings

To apply the MSN for the underlying case study, various parameters have to be set. Some parameters are derived from previous studies, for example, the estimated travel preferences from a large-scale stated preference experiment conducted in the Netherlands (Arentze and Molin, 2013), while others are more based on more general insights provided by Dutch transportation organizations like the Ministry of Transport and Water Management. Table 2 shows the location choice parameter settings in Eq. (2) for prior selection of activity locations and defining the traveling to conduct flexible activities based on findings of Liao et al. (2017). For ease of implementation, the attractiveness of an activity location is indicated by the floor space.

Second, various road types and corresponding travel speeds have to be defined. The road type subdivision aims to pursue a better detail of policy assessment. Furthermore, the time-dependent component is added by varying the speed profile during peak hours or off-peak periods during a weekday to represent the potential road congestion and increased travel time on the road. Within the study area, we have adopted a detailed subdivision setting of road sections defined by Maas (2015), in which the road types are categorized based on 6 different maximum speed profiles and fuel consumption (Table 3).

Various parameter settings of the MSN approach are needed. The original settings are based on a demonstration of the micro-simulation in the Rotterdam area (Netherlands) (Liao et al., 2017). Some parameters are adjusted to fit better in the current time period and the study area of the Metropolitan area of Eindhoven. First, the fuel cost per liter is adjusted for the up-to-date situation based on the average price trend in the past five years in the Netherlands (GlobalPetrolPrices, 2020). Second, to connect the road network segments and junctions with the public transport stops within the study area, the real distances are calculated rather than estimated by the geo-coordinates. Third, the thresholds of various distances for search flexible activity locations and switching mode have been adapted to the study area. The updated and revised internal parameter value settings for model estimation are presented in Table 4.

3.4. Policy scenarios

Combining the LRT developments and parking price adjustments, ten different policy scenarios are generated (Cheng, 2020). In the remainder of this article, the focus is put on the six scenarios dealing with separate LRT lines. A seventh scenario is added to show the effect of all measures together. All scenarios are compared with the base situation (S0). The first three scenarios (S1, S2, and S3) deal with each new LRT line separately. In the next three scenarios (S4, S5, and S6), the three new LRT lines are considered separately in combination with parking price policies. The final scenario (S7) includes all three LRT lines with corresponding parking policies. Table 5 shows an overview of the seven policy scenario inclusive settings for modeling applications using the MSN. Finally, Table 6 shows an overview of the final settings used in the simulation.

To achieve the objective of reducing car vehicle usage and improving transit efficiency, the parking price adjustments are applied to the municipalities that have new LRT lines crossing the administrative region. Thus, different LRT lines affect the parking price in particular municipalities. The parking price adjustment is based on the current price level during a typical weekday in several Dutch major cities with LRT systems

Table 2
Individual flexible activity location preference parameters.

Field explanation: Coefficients for activity location attractiveness		Weight values
Distance to location (km)	Parameter FromDist – Shopping activity	1.78
	Parameter FromDist – Going-out (Meeting/ Visit)	1.35
	Parameter FromDist – Recreational tour (Visit/Lodge)	1.67
Floor space (km^2)	Parameter Size – Shopping activity	0.23
	Parameter Size – Going-out (Meeting / Visit)	0.232
	Parameter Size – Recreational tour (Visit / Lodge)	0.101

Table 3
Road types division and parameter settings*.

Subdivision		1	2	3	4	5	6
Road type or locations		Local roads Residential	Radial roads Regional roads Inner-city area	Ring roads Rural area Airport area	Access roads Highways (N-roads)	Motorways (A-roads)	Bicycle path Inner-city path
Maximum speed	Car	30 km/h	50 km/h	70 km/h	100 km/h	120 km/h	(Not allowed)
	Bike	12 km/h	15 km/h	20 km/h	(Not allowed)	(Not allowed)	10 km/h
Fuel consumption (Car average speed)*		10L/100 km	8L/100 km	7L/100 km	6L/100 km	6L/100 km	–
Link counts		38,818	16,434	16,270	10,434	8,522	426

* This information is only used for determining route choices, not for calculating the emission index.

Table 4
Parameter settings of MSN model.

Public transport cost

PT type	Intercity train	Stop train	Light-Rail	Bus
Euro/min	0.30	0.20	0.17	0.15

Other settings

Parameter	New value
Walk speed	5 km/h
Fuel cost (car)	1.6 Euro/Liter
Driving margin (meter)	60 km
Search distance for nearby flexible activity location from previous activity	7 km
Search distance for nearby activity location from home (activity-depend)	50 km
Walk preferred distance than the bike	0.3 km
Walk preferred distance than a car	0.4 km
PT preferred distance over a car	60 km

Table 5
Policy scenario combination settings for model application.

Scenario ID	Scenario combinations	Descriptions
S0	S0	Base scenario
S1	S1	LRT Line A development only (A)
S2	S2	LRT Line B development only (B)
S3	S3	LRT Line C development only (C)
S4	S1 + P	Line A with parking-related policies (A + P)
S5	S2 + P	Line B with parking-related policies (B + P)
S6	S3 + P	Line C with parking-related policies (C + P)
S7	S1 + S2 + S3 + P	LRT Lines A, B, and C with parking related policies (ABC + P)

Table 6
Policy scenario input data settings for model application.

Scenarios	Road network	Land-use locations	Parking price policy implemented area	P + R locations	Light-Rail lines
S0	Nodes:	Activity	0	0	0
S1	31,663	locations:	0	0	1
S2	Links:	27,388	0	0	1
S3	90,904	(8 activity	0	0	1
S4		types)	5 municipalities	5	1
S5			4 municipalities	4	1
S6			3 municipalities	3	1
S7			10 municipalities	12	3

in operation (Prettig Parkeren, 2020). In the four major municipalities of the study area (Eindhoven, Helmond, Den Bosch, and Tilburg), the base cost regarding the parking price of the inner-city areas is increased to 1.5 Euro while the unit cost is increased to 3 Euro per hour. For the parking price of the district centers, the base cost is decreased as 1 Euro while the unit cost is increased to 2 Euro per hour. Table 7 compares the parking price settings between the base scenario and the new parking price policy implementation.

The parking-related policy also includes several Park and Ride (P + R) facilities at the beginning/ending of the LRT lines. The locations are connected to existing public transport stations, existing P + R locations, and/or exits of highways. Based on the current price level of P + R facilities in the Eindhoven municipal area (Prettig Parkeren, 2020), the parking price of these newly developed facilities will be set to be lower than the cost of inner-city and district center areas for attracting potential transit users. The development of these facilities aims to provide an option for travel mode transferring and to promote the new urban public transport system. Therefore, every P + R facility of the LRT node is considered as both B + R (Bike and ride) and C + R (Car and ride) location. However, due to the multi-state supernetwork model's limitation, the capacity constraints of these facilities are not considered. Travelers who choose the facility as a parking location will not influence other travelers' decision during the simulation process.

4. Results

Running the MSN-based evaluation approach produces multifaceted indicators. Given the focus on mobility and environmental effects, the description of results covers four different topics: travel patterns, travel mode distribution, route choice patterns (heat maps), and emission effects.

4.1. Travel patterns

The effects regarding the *travel patterns* are presented (Figs. 5-7) with a focus on the LRT lines and the suggested parking policy. Considering the LRT lines alone, both Line A and Line B contribute to a slight reduction in individuals' average travel distance (Fig. 5) and travel time (Fig. 6) of all included travel modes. The result implies that a small part of the population shifts their mode choice using Line A or B, resulting in a slight reduction in travel time and distance. With the introduction of Line C, although some people shift their mode and route choice as well to improve utility, the shift does not lead to a reduction in travel time and distance. With the implementation of the parking price policy and P + R facilities (Scenarios S4-S6), the reduction effects are considerable for Lines A and B, indicating that a larger part of the population adapt their mode choice. These mobility indicator results have proven that in the investigated scenarios the parking-related policies are more effective and influential compared to public transport development itself on affecting travel patterns. In contrast, the effects of alternative LRT Line C are not as expected; the LRT line itself does not lead to a reduction of the average travel distance and time because of extra car/bicycle use. Compared with other alternatives (Line A or B), Line C option even increases the individuals' travel distance and travel time due to the newly developed infrastructure. In detail, the individuals spend more time and travel longer distances by car or by foot to reach the new LRT facilities of Line C while spending less travel time on public transport, especially for the residents in the broader metropolitan area. However, since the travel mode share of PT is relatively small compared to other modes, the reduction of PT travel time has been offset by the increase in private

Table 7
Parking profile setting adjustments (Prettig Parkeren, 2020).

Parking price settings							
Location category			(1) Inner City	(2) District center	(3) Others	(4) Airport area	(5) P + R facility
(S0) Base scenario	Car parking	Base cost	1.0 Euro	1.5 Euro	Free of charge	4.0 Euro	Not included
		Unit cost	2.5 Euro/h	1.5 Euro/h	Free of charge	Daily tariff	Not included
(S4-S7) Parking price policy		Base cost	1.5 Euro	1.0 Euro	Free of charge	4.0 Euro	1.0 Euro
		Unit cost	3.0 Euro/h	2.0 Euro/h	Free of charge	Daily tariff	0.5 Euro/h

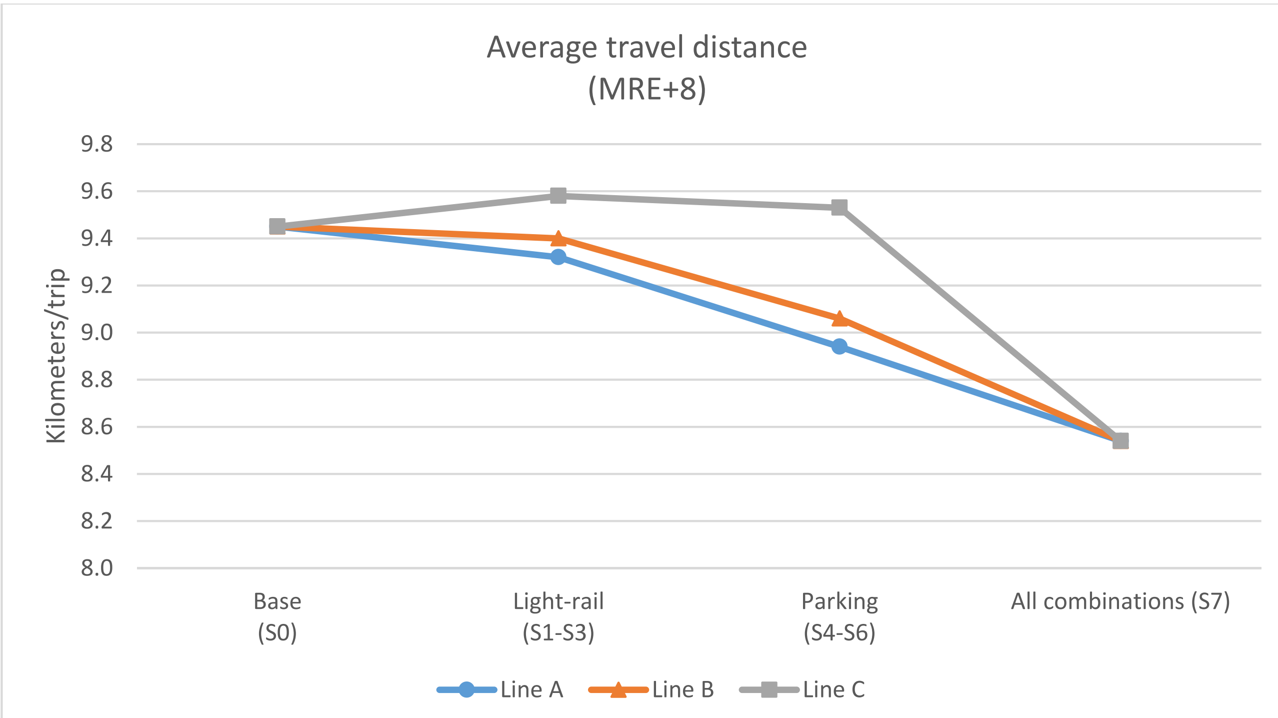


Fig. 5. Travel pattern effects of scenarios S0 until S7: Average travel distance.

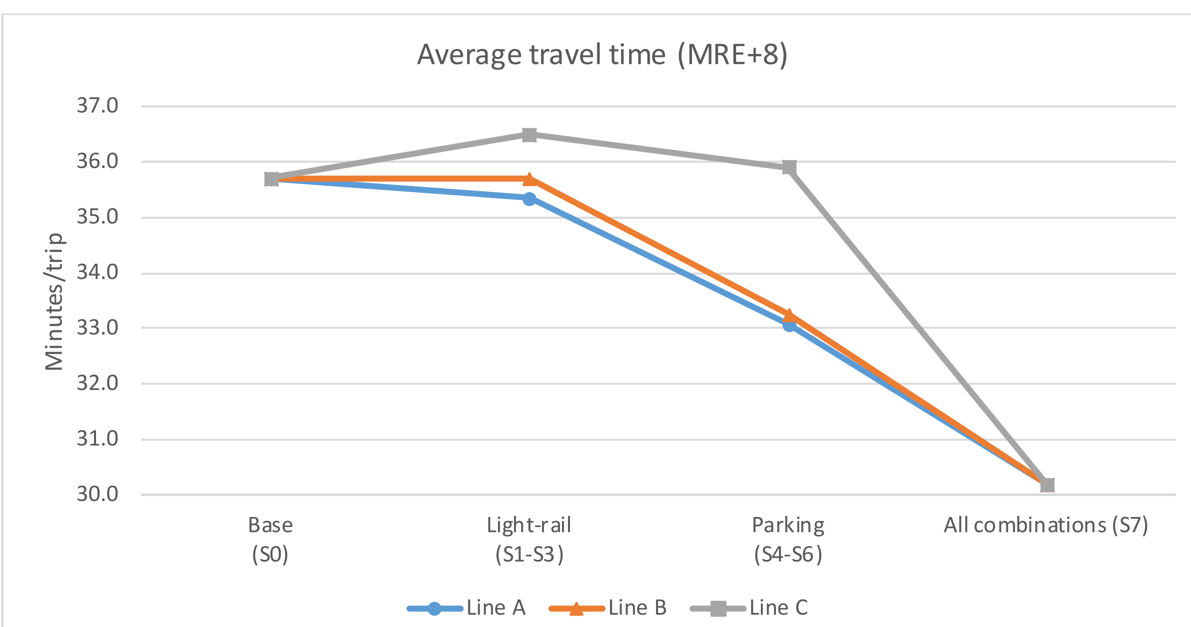


Fig. 6. Travel pattern effects of scenarios S0 until S7: Average travel time.

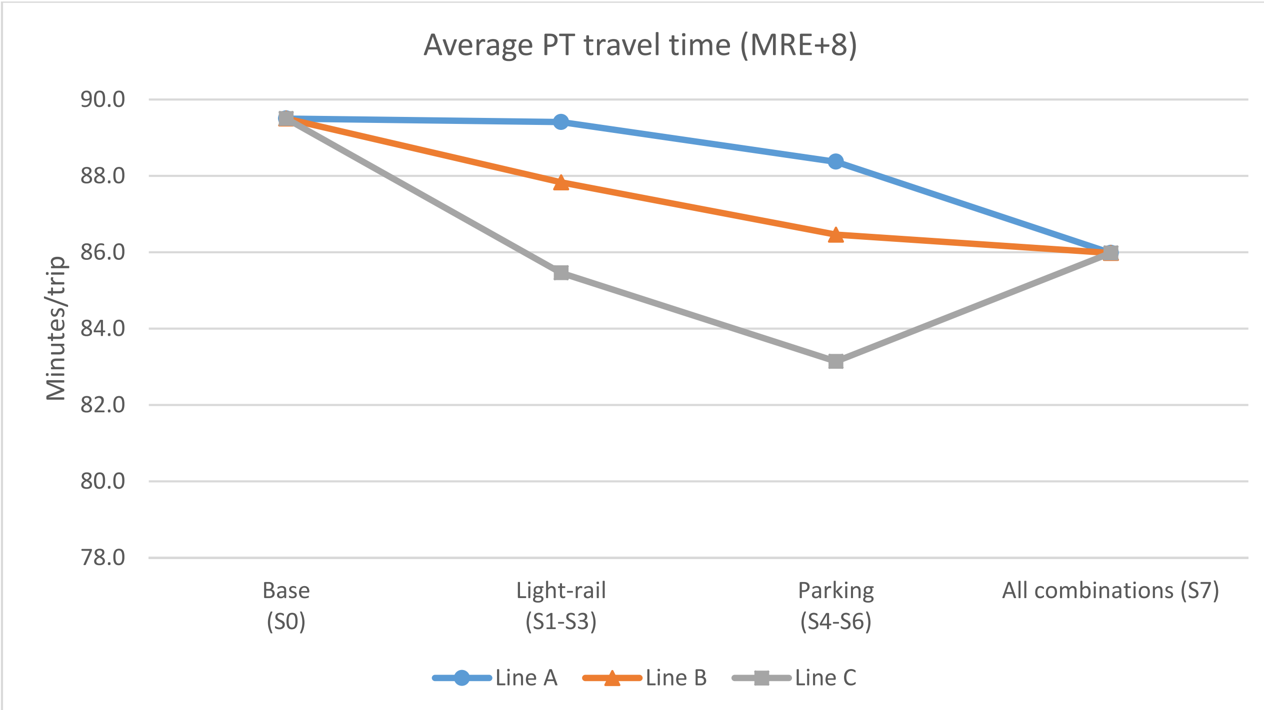


Fig. 7. Travel pattern effects of scenarios S0 until S7: Average public transport travel time.

travel modes or by walking.

4.2. Travel mode distribution

The simulated results of *travel mode distribution* among all scenarios are presented in Fig. 8. No matter which LRT alternative (Line A, B, or C) is realized in the study area, the modal split of traveling means is more or less similar compared with the base situation. It has indicated that the parking-related policies are slightly more effective to stimulate the travel mode shifting from using private car vehicles into choosing bike mode or public transport, especially for Line A and Line B developments (S4 and S5). The introduction of Line C and parking-related policy in S6 does not stimulate the intended shift from car use to PT use. Although some travelers use Line C (Fig. 9), these travelers were probably PT users

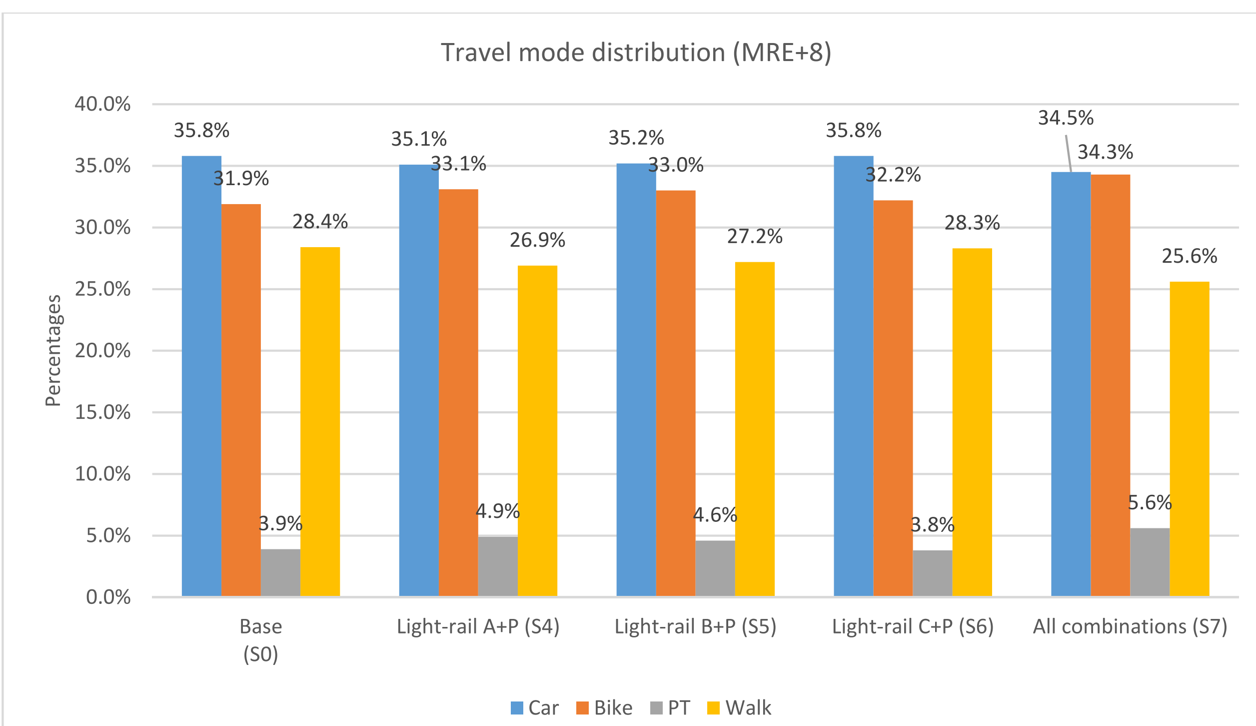


Fig. 8. Travel mode distribution for scenarios S0 and S4 until S7.

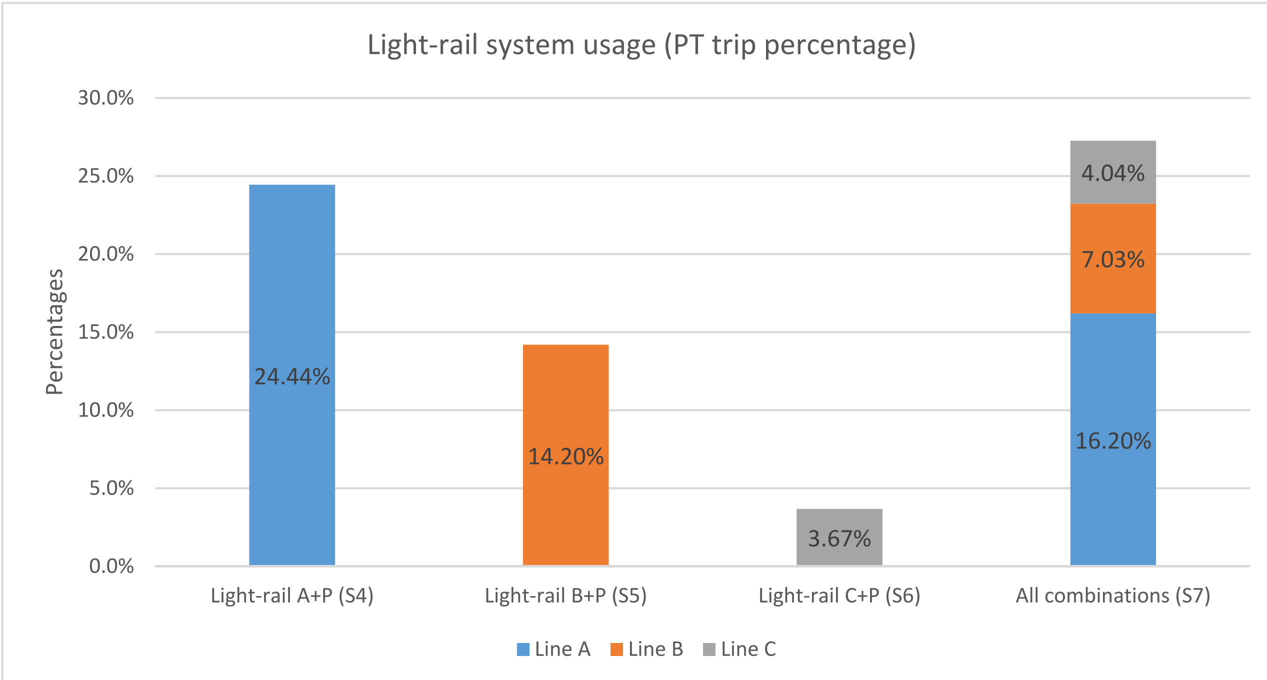


Fig. 9. LRT use for scenarios S4 until S7.

before S6 is introduction. However, it should be noticed that a slight shift from car use to bike use is observed mainly because of the parking-related policy. Therefore, the main cause for an increased market share of public transport is caused by the introduction of LRT lines A and B (Fig. 9).

4.3. Route choices

GIS heat maps are utilized to visualize and address insights into the spatial effects of *individuals' route choices by car* in the daily activity-travel patterns (Fig. 10). The maps show the increase (red) and decrease (blue) in road usage by car. Initially, the route choice effects are compared between the LRT development scenarios that have parking-related policies implemented (S4-S6). As expected, in comparison with the base situation, the road network usage near the new LRT stations increases (red) while inner-city areas or district centers decrease (blue). As it could be expected for cars, this influence is more apparent with the stations that have P + R facilities included with a lower parking price level compared with inner-city areas or district centers. It should be noted that the research did not consider the facility's occupation or parking space limit for the sake of evaluating the potential effects. This simulation output of travelers' agglomeration around the P + R facilities has confirmed the parking policy-sensitive characteristic of the applied MSN approach.

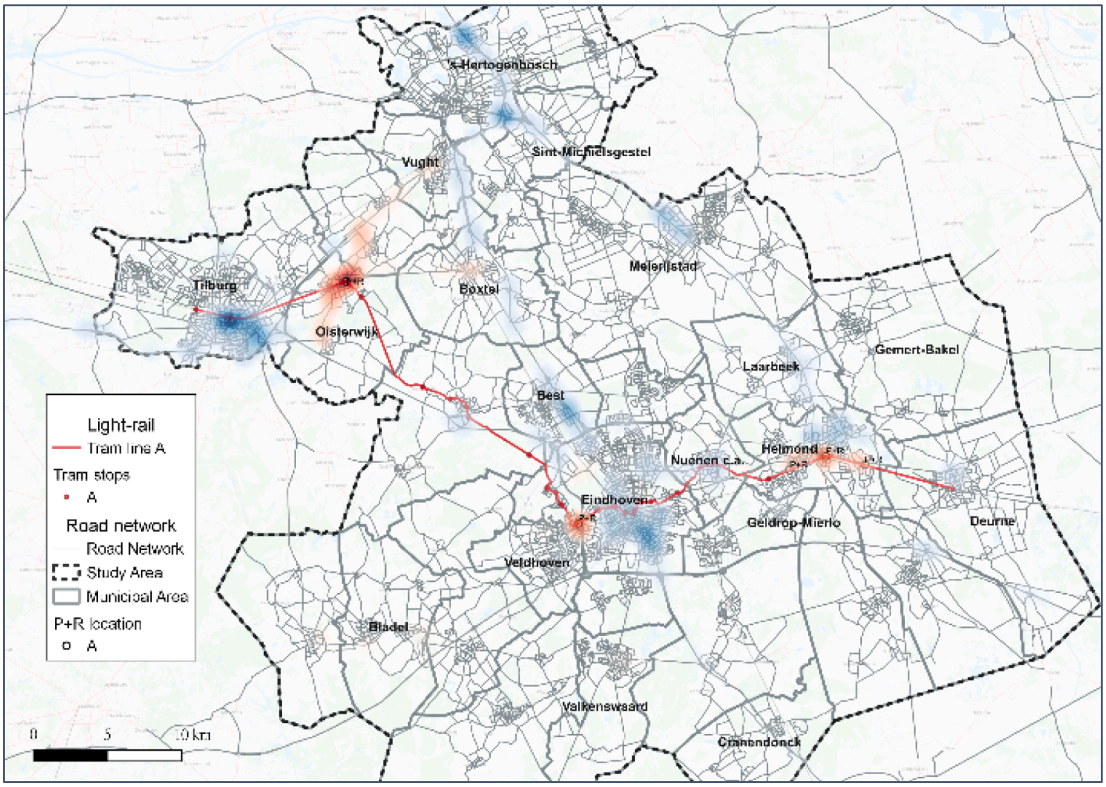
In more detail the maps presented in Fig. 10 show the following. Based on the observations of Fig. 10a (S4), LRT line A with parking-related policy has reduced the car travel of the inner-city area in the three major municipalities (Eindhoven, Tilburg and Helmond) that have implemented parking price adjustments. However, the inclusion of P + R facilities has largely increased road usage in the nearby region for both car and bike travel modes such as the station area in the municipality of Oisterwijk, Meerhoven, and Helmond station area. According to Fig. 10b (S5), LRT line B with parking-related policy contributes to the decrease of road usage with car travel in the Eindhoven inner-city area. Besides, an interesting route choice shifting effect of car travel mode is observed in the municipal area of Den Bosch in the north. Car travel in the Northern region of Den Bosch where a major motorway interchange (between A2 and A59) is located, has a substantial decrease while car travel in the central station area of Den Bosch has a significant increase. Similar to the route choice effects of scenario S4, the inclusion of P + R facilities in the scenario has attracted more car and bike trips nearby the surrounding region. As for the LRT development with the parking-related policy of LRT line C, Fig. 10c (S6) shows that both car and bike travel is reduced within the city center of Eindhoven. However, car travel is increased nearby the motorway interchange of A2, A50, and A67. Also, the effects of P + R facilities lead to an increase in both car and bike travel in nearby regions.

Finally, Fig. 10d shows the road usage heatmap of the road use by cars for all LRT lines and parking-related policies. Based on the observation, there is a considerable decrease in road usage by car travelers in the city centers of Eindhoven and Tilburg. Other municipalities such as Helmond, Best, and Meierijstad have a slight reduction in road usage by car travelers in their main station area. The effects in these municipalities are expected since most of them have implemented the parking price adjustment in both the inner city and district center area. Also, some motorway interchanges have observed less road usage such as A2/A59 and A2/N279 in Den Bosch and A2/A67 on the South side of Eindhoven. On the other hand, the P + R facilities' effect on increasing road usage is still considerable in certain new LRT station areas, such as Den Bosch Central Station, Oisterwijk station, Boxtel station and P + R Meerhoven. The lower parking price of these P + R facilities has attracted car users to park at the newly developed P + R facilities and transfer with public transport alternatives.

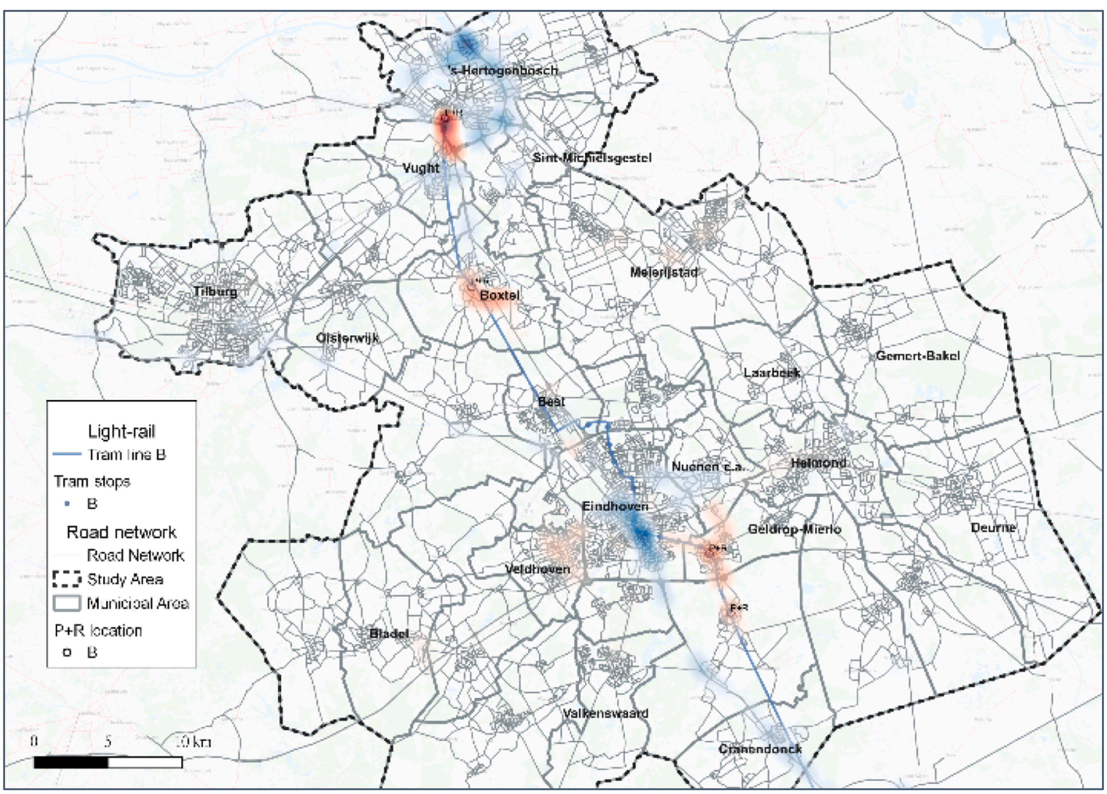
4.4. Emission effects

The final results concern the emission effects of air pollutants after the LRT developments and parking policies are realized (Fig. 11). Comparing the travel pattern results of all scenarios, the LRT infrastructure with parking policies that have a substantial reduction in car travel (S4 and S5) has also contributed to the lower total amount of air pollutants emitted. Also, the LRT developments benefit the environment at the larger metropolitan region level instead of only the Eindhoven municipality in terms of the emissions on roads by car vehicles (see Fig. 11).

In addition, Fig. 12 displays the calculated EHI results for all

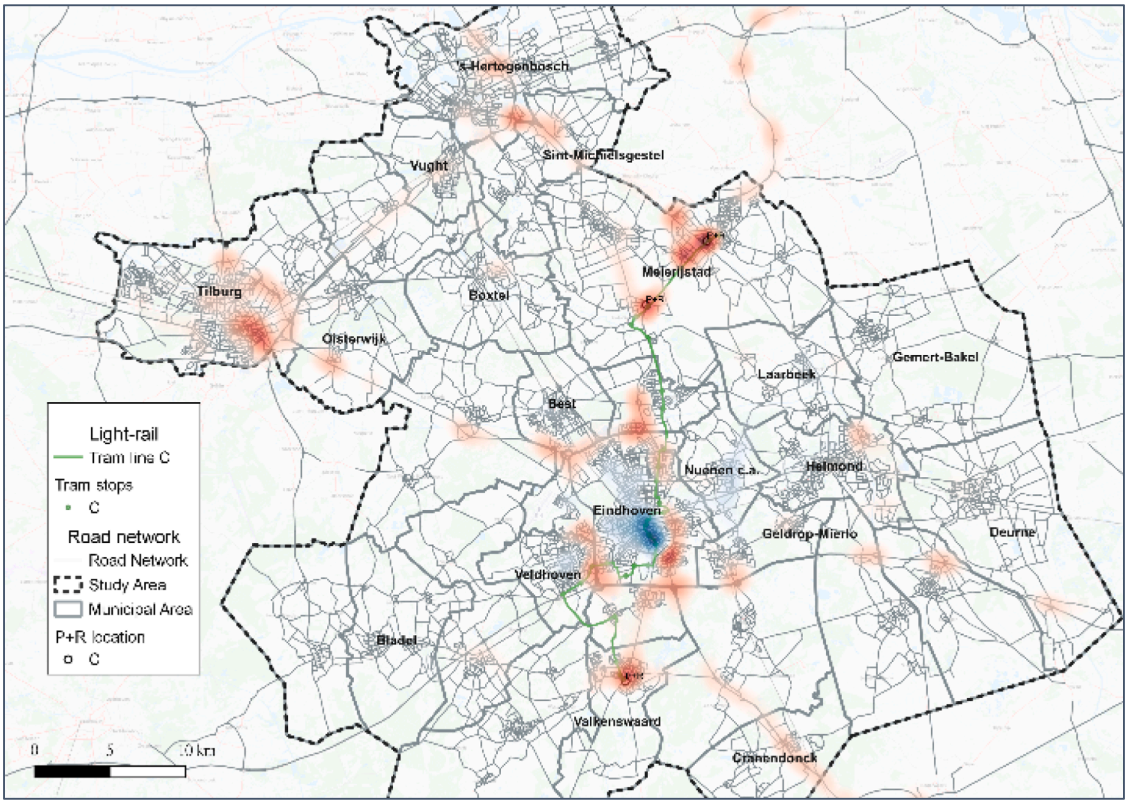


(a) *Heat map of individuals' route choices by car, scenario S4*

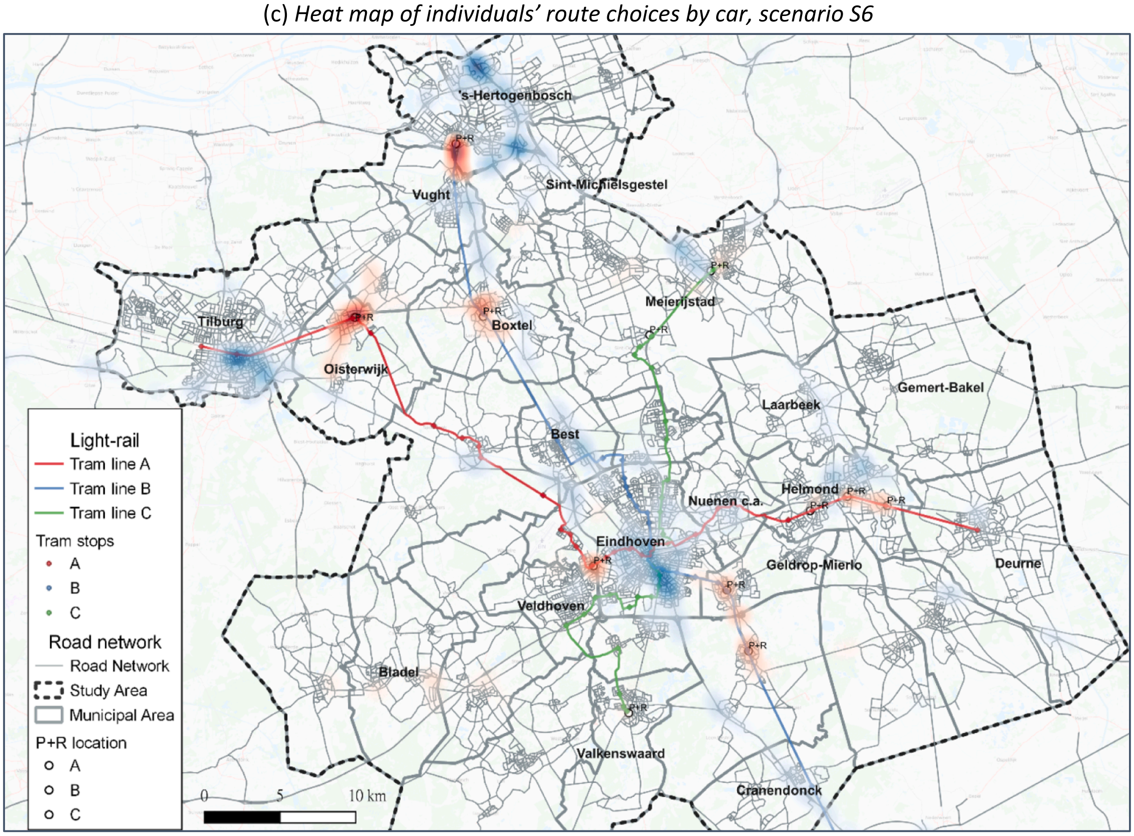


(b) *Heat map of individuals' route choices by car, scenario S5*

Fig. 10. Heat maps of individuals' route choices by car, respectively scenarios S4(a), S5(b), S6(c), and S7(d).



(c) *Heat map of individuals' route choices by car, scenario S6*



(d) *Heat map of individuals' route choices by car, scenario S7*

Fig. 10. (*continued*).

scenarios including the ones highlighted in this paper. Based on the observations, it is apparent that LRT developments with parking-related policy implementation (Scenarios S4 and S5) have a better effect on improving the air quality shared by the population. With the integration with policy measures such as parking price adjustment and P + R facilities, the average PM2.5 equivalent per study area resident is 0.1 kg

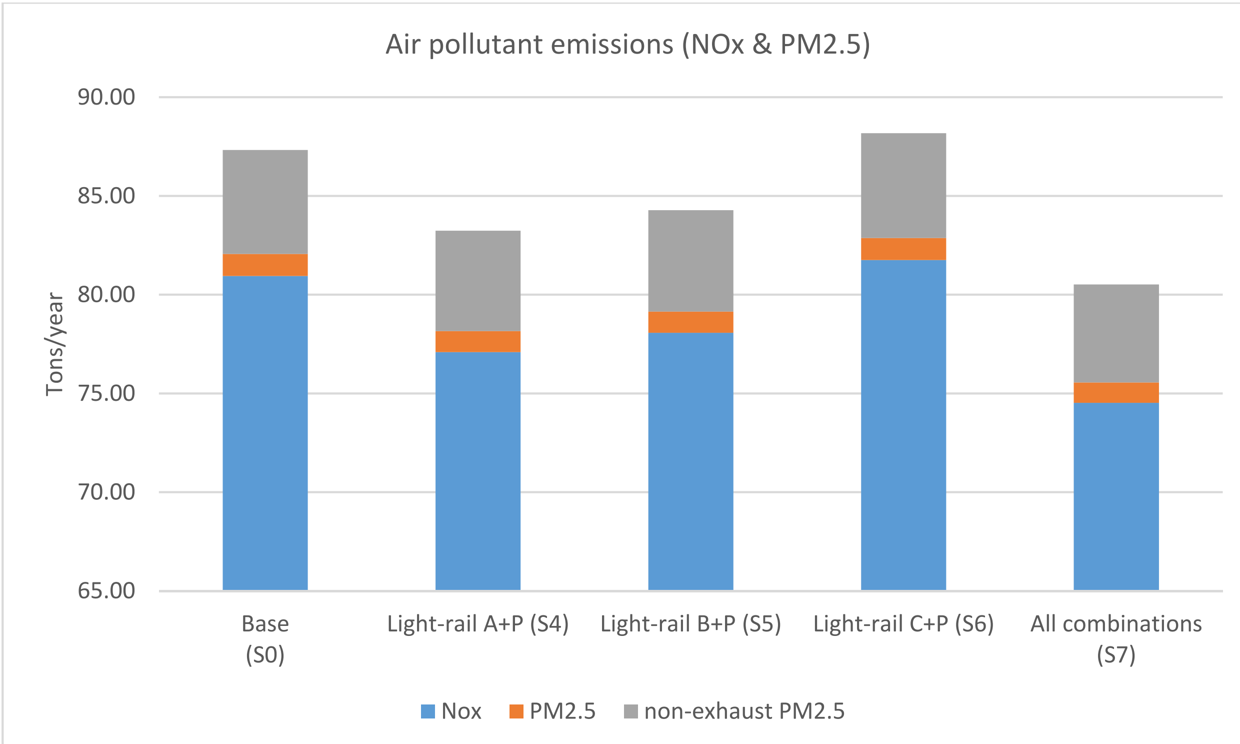


Fig. 11. Total air pollutant emissions for MRE + 8 region.

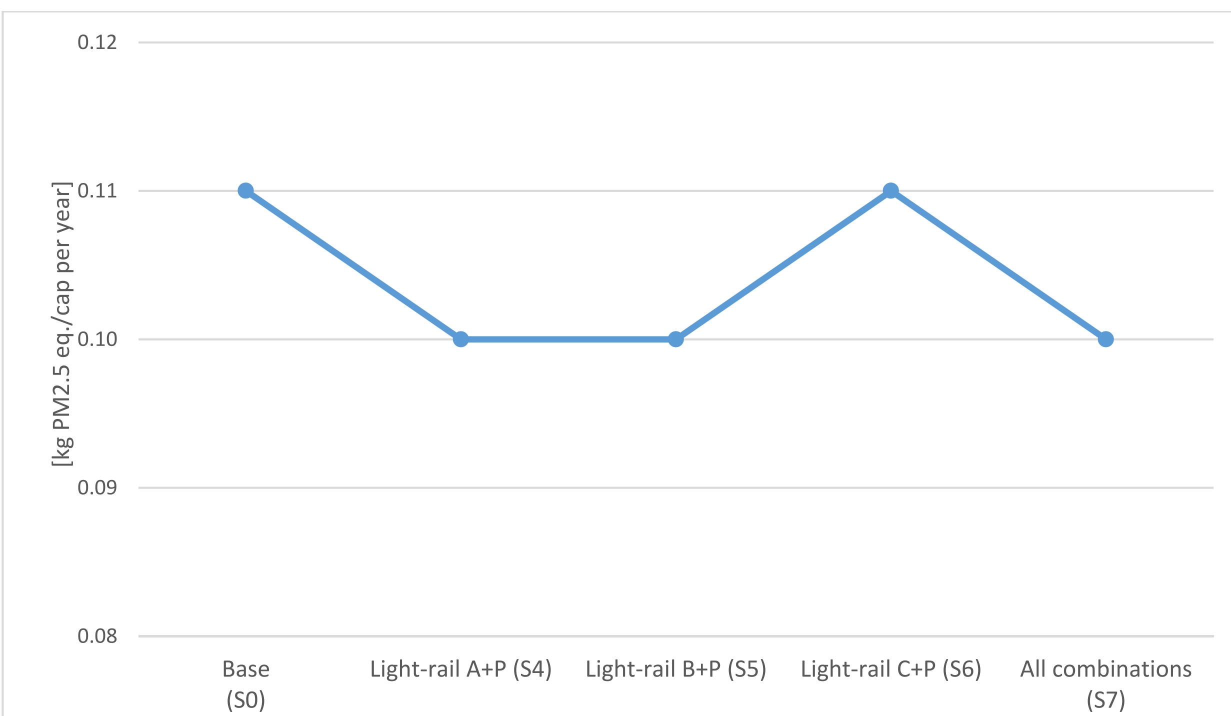


Fig. 12. Emission Harm equivalent Index for the MRE + 8 region.

per year which is lower than the average amount in LRT scenarios without any parking-related policy. The effect might be caused by the fact that these lines are within high-density areas providing residents with sustainable transport at a short distance. As expected based on the results presented before, for Scenario S6 (Line C and parking policies) no improvement is noticed. This might be related to the fact that this line is mostly located in rural areas where travelers have to travel some distance to arrive at LRT stations. Combining all scenarios with corresponding parking policies (S7) gives the largest reduction of air pollutant emissions.

5. Discussions

Research about travel behavior in the urban environment is considered essential for assisting land-use transport policy decision-making (De Bruijn & Veeneman, 2009). Emerging mobility concepts can change the way people travel and require advanced research methods to capture behavioral effects. Travel behavior modeling can provide rich and useful insights into various mobility concepts in the urban mobility system. The results found in this study provide detailed information regarding three different extensions of the Metropolitan LRT system in the Region of Eindhoven, the Netherlands. The results show how travel behavior changes and where these changes take place, giving practitioners handles to focus attention to specific travel modes and locations in the region.

The different MSN simulations show that the introduction of the LRT Line A and Line B in the extended Metropolitan area of Eindhoven will result in a small decrease in the overall average travel time and the overall average travel distance (including both car and bicycle trips). The average travel time by public transport decreases showing that destinations become more accessible by public transport. The most beneficial line in this context is Line C where a regional bus connection is replaced by a metro line with a more direct connection and a higher average speed. All effects become bigger when the LRT is introduced in combination with parking policies. To achieve the highest effects of the new LRT development, it is best to start with building Line A followed by Line B both in combination with parking measures. Besides improving the accessibility of locations by public transport and influencing parking-related aspects, both LRT options will also decrease the level of air pollutant emissions and the demand for car-related infrastructure in the inner-city areas. The area that becomes vacant due to lower demand for infrastructure can be used for other types of land use. When deciding what kind of land use fits best at various locations, it is also worthwhile to look at the changes in air pollutant emissions because of changes in travel demand due to new land uses. In contrast, due to increasing demand for Public Transport and in addition, infrastructure for access modes, the infrastructure for cars and bicycles around LRT stations and P + R has to be extended.

The comprehensive approach used in this study supports strongly the decision-making process at the regional level by including various local and regional settings such as transportation network, land use, and travel demand. Various studies indicate the importance of a more regional look when considering the future of public transport. LRT is seen as efficient and reliable public transport designed for high volume public transport serving at local, metropolitan, and regional scales (Van der Bijl & Van Oort, 2014). For regional trips, the car is still the most dominant travel mode (Rye & Hrelja, 2020). Also in the Dutch government's vision for the future, special attention is paid to public transport-related regional developments including combining high-frequency services in and around cities, integrating regional mobility by public transport hubs, and increasing sustainability of public transport by emission-free, safe, and efficient public transport system (Ministry of Infrastructure and Water Management, 2019).

The approach also fills in the identified need for more comprehensive methods at the regional scale to get better and more detailed and quantitative insights into potential travel behavior related effects of light rail projects (De Bruijn & Veeneman, 2009; Van der Bijl & Van Oort, 2014; Donners & Hannema, 2019). Together with technical, economical, and environmental insights, insights into future travel behavior are relevant when answering the question 'why' LRT should be considered as efficient and effective public transport system in the region (Van der Bijl et al., 2018). In addition, making a connection between LRT developments and local and regional needs and processes can speed up decision-making processes (De Bruijn & Veeneman, 2009). Therefore, the most interesting benefit of the presented approach is showing changes in local and regional traffic movements including their effect on environmental quality. The study also shows clearly that the accessibility to locations, both in terms of distance travelled and time used, does not decrease when introducing new public transport-related services.

6. Conclusions, limitations, and future work

Mobility visions and strategies are under discussion to relieve the capacity bottlenecks of the current transport system. LRT has been promoted as an effective solution toward sustainable transportation in urban areas. To assess the travel pattern and environmental effects after the LRT is realized, an activity-based travel demand model multi-state supernetwork is adopted. During the application of this innovated and improved approach, air pollutant emissions have for the first time been incorporated with the aggregated trip results of the modeled output. The case study focuses on the changes in individual travel patterns and emitted air pollutants after seven scenarios of the LRT system are realized in the extended Eindhoven Metropolitan Region. The mobility indicators of travel pattern effects provide fruitful information and insights for LRT infrastructure planning and parking-related policy-making. Besides, an emission module with air pollutant effects further supports the policy-making by evaluating environmental impacts on the study area. Comparing the scenarios with the base scenario, it is found that the scenarios combining LRT, parking pricing policy, and P + R perform better than scenarios with a LRT extension only. In addition, LRT lines A and B perform best when looking at travel patterns, travel mode distribution, route choice patterns (heat maps), and emission effects.

Nevertheless, the present study has serval model limitations. First, although the sampled size of the synthesized population has composed around 8 % of the actual population size, it may be still considered insufficient for generating realistic vehicle flows at a micro-level of traffic impact for evaluation projects. Second, the present MSN application lacks the feedback of the resulted macro states on individual scheduling behavior and the interactions between the individuals during the simulation. Therefore, even if the population size with the actual scale is comparable to the real-world situation, the user equilibrium mechanism for aggregating each road's traffic status is not currently incorporated with the operating micro-simulation system. Third, this research did not include land-use development regarding the LRT policy scenarios, although it is considered as an essential or common component together with introducing a new public transport system. These related developments often concern new residential or industrial floor space that might simultaneously influence the residential and employment decisions of individuals within or outside the study area. Without a reliable or demographic-based generator unit for the synthetic population, the decision was made to exclude the land-use developments and only consider the LRT infrastructure and parking-related policies.

Despite the model limitations, the MSN approach has proven its predictive power on an individual's activity-travel patterns by simultaneously considering multi-dimensional choices and representing complete trip-chaining. With the new emission effect dimension incorporated, the recommendations for future research and model improvements for enriching the mobility or environmental aspects of policy assessment are suggested. First, with the developments in energy sources and different types of motor engines in transportation sectors, a better-detailed categorization of these fuels regarding consumptions per distance unit or emission standard of air pollutants is suggested to consider for estimating a more realistic emission effect. Also, with a detailed specification on fuel categories or emission levels, more aspects of environmental effects such as greenhouse gas (GHG) or more types of emitted pollutants based on scientific reports are recommended. Second, apart from evaluating the emission effects at an aggregated level or yearly amount, the air pollutant amount should also incorporate the activity trip-table output regarding the temporal components. Considering the micro-level of an individual's travel patterns, the model has opened the possibility to evaluate the temporal distribution of air pollution effect through the time of day. Third, to systematically evaluate the metropolitan LRT system proposals, a cost-benefit analysis should be further suggested. By giving weights to different stakeholders' objectives and monetarized value of mobility or environmental effects, the decision-making of LRT projects can be supplemented.

7. Authors' statement

The authors confirm contribution to the paper as follows: study conception and design: P. van der Waerden, Y. Cheng, and F. Liao; data collection: Y. Cheng; analysis and interpretation of results: P. van der Waerden, Y. Cheng, and F. Liao; draft manuscript preparation: P. van der Waerden and F. Liao. All authors reviewed the results and approved the final version of the manuscript.

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