TECHNICAL TRANSACTIONS 6/2018
CIVIL ENGINEERING
DOI: 10.4467/2353737XCT.18.090.8695
SUBMISSION OF THE FINAL VERSION: 08/06/2018

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The impact of long-term travel demand changes on mixed decision problems of mass transit lines construction and vehicles' depots location

Wpływ długoterminowych zmian popytu na problem jednoczesnego wyznaczania przebiegu linii i lokalizacji zajezdni w systemie transportu zbiorowego

Abstract

The paper is concentrated on solving a mixed decision problem of mass transit line construction and vehicles' depots location (MTLC&VDL). The authors have iteratively solved this problem as a function of scenario-based, long-term travel demand changes, and finally have analysed the generated results. As a product of the computations, it has been proved that the solution of the mixed MTLC&VDL decision problem depends on changes in travel demand, both in terms of the line construction and the location of the depot. 5 and 10% increase of travel demand leads to changes in the optimal mass transit line's configuration, while the change of the optimal depot location takes place with 10% of the travel demand change. The results have implied a conclusion that to make strategic decisions on transport systems and solving mixed decision problems, forecasting travel demand changes (its volume and structure) over the long-term horizon has to be performed.

Keywords: mass transit lines construction, vehicles' depots location, travel demand, exact optimisation, traffic modelling

Streszczenie

Artykuł dotyczy łącznego rozwiązania dwóch problemów decyzyjnych związanych z systemem publicznego transportu zbiorowego, tj. wyznaczania przebiegu linii transportowych (MTLC) oraz ustalania lokalizacji zajezdni transportowych (VDL). Autorzy zastosowali iteracyjne rozwiązanie obu problemów, zakładając różne scenariusze długoterminowych zmian popytu oraz przeanalizowali uzyskane wyniki. Jak dowiodły obliczenia, rozwiązanie połączonego problemu MTLC i VDL zależy od zmian popytu. Wzrost popytu o 5 i 10% skutkuje zmianą optymalnego układu linii transportu zbiorowego, podczas gdy do zmiany optymalnej lokalizacji zajezdni dochodzi przy zmianie popytu na poziomie 10%. Wyniki prac pozwoliły wnioskować, że do podejmowania strategicznych decyzji dotyczących systemów transportowych i rozwiązywania mieszanych problemów decyzyjnych należy prognozować zmiany popytu (jego wielkość i strukturę) w długim horyzoncie czasowym.

Słowa kluczowe: publiczny transport zbiorowy, przebieg linii transportowych, lokalizacja zajezdni, modelowanie podróży

1. Introduction

1.1. Travel demand

Travel demand changes derivate from both, external phenomena such as: transport behaviours, demographics, etc., and strategic development of the region, including spatial development, investments and macroeconomics, etc. The land use characteristic is the main issue influencing trip generation rates. This is because factors like the number and size of households, automobile ownership, types of activities (residential, commercial, industrial, etc.), and density of development all drive how much travel flows from or to a specific area within the region. Changes to these factors can affect travel activity and therefore costs and problems such as congestion, accidents and pollution emissions.

The wide range of factors that influence travel activity is especially important for transportation demand management (TDM). The Federal Highway Administration [8] defines TDM as providing travellers with travel choices, such as work location, route, time of travel and mode. In the broadest sense, demand management is defined as providing travellers with effective choices to improve travel reliability. Therefore, a reduced demand for motor vehicle travel (or at least, growth in demand) and an increased demand for alternative modes are crucial.

1.2. Mass transit line construction and vehicles' depots location

A strategic decision considered in the paper is related to mixed decision problems of the mass transit line construction – MTLC and vehicles' depots location – VDL. The essence of combining these two strategic problems (MTLC&VDL) is to find a solution that guarantee the required standards for passengers (maximised availability) offered at the lowest operating costs for the operator (minimised deadhead). In fact, the nature of each separate decision problems is contradictory while considered together. The problem of MTLC is strongly dependent on travel demand. The lines' routing is highly related to the areas characterised by significant volumes of traffic production and attraction, and thus related to a high density of population. On the other hand, the VDL problem refers to setting all technical facilities related to the operation of the operated fleet. In order to minimise empty runs between transport lines and depots, they should be located as close as possible to each other. Due to the amount of space demanded for the proper depots' operation and market value of parcels, however, a less urbanised location (with less cost of acquisition at the same time) is usually searched for. Thus, a contradiction of those decisions means that a reduction of investment costs is directly translated into an increase of operating costs of empty runs (depot-line) at the same time, and vice versa.

The result of the research on joint consideration and solution of the mixed MTLC&VDL decision problem has been presented by the authors [13, 14] before. The principle of this methodology is a combination of the construction of four-stage traffic modelling with the construction and application of a single-criterion mathematical model solved with the use of exact optimisation algorithm. Each individual step of the methodology is iteratively repeated until a globally satisfactory solution is obtained. The schema of its dependence is presented in Fig. 1.

In the methodology of modelling and solving mixed MTLC&VDL decision problem, the current travel demand volume is assumed, and it is unchangeable for a considered single time period. This volume is consistently applied into all consecutive computations.

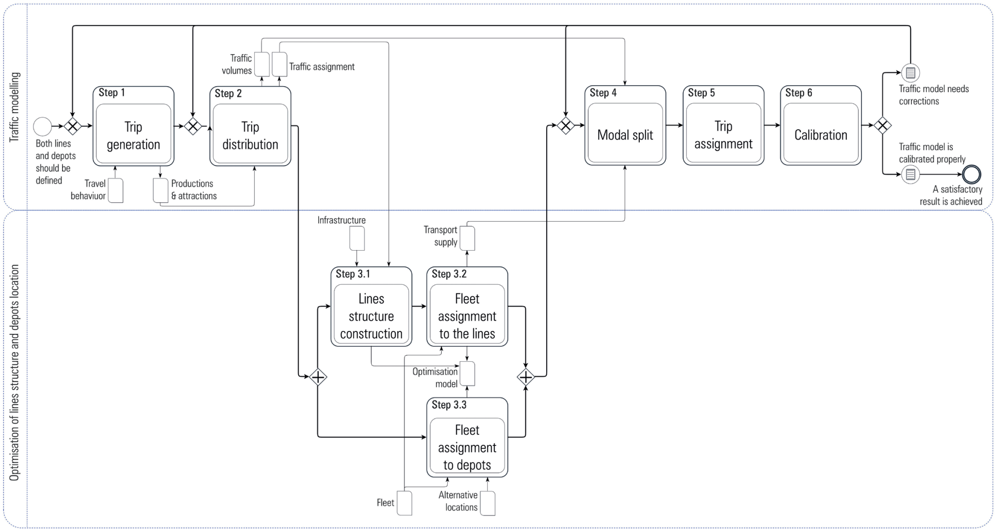

Fig. 1. Key steps of the methodology of solving mixed MTLC and VDL decision problems [14]

1.3. Current state of the decision problem

MTCL is a one of the fundamental decision problems in the mass transit research domain. It has been widely discussed in the literature, either in works on the principal concepts from the last century, e.g. Baaj & Mahmassani [2], Dial & Bunyan [6], Dubois et al. [7], or from the recent period, e.g. Ceder [5], Schöbel [15], Teodorović & Janić [17], Abdallah [1]. In this research, MTCL is concentrated on building a mass transit network with a simultaneous determination of other associated issues, including the frequency of running (e.g. [4, 16]), transferring to other lines at the stations [12] and others.

VDL, as a decision problem, has not been extensively discussed in the literature on mass transit research domain. This problem with references to the bus depots location has been analysed by Hamdouni et al., [9, 10], and with reference to the tram network by Kupka & Sawicki [11]. The main assumption in such a research is an unchangeable structure of routes. A simultaneous consideration and solution of depot location and routing problems is a very common approach in the freight transportation research domain. In the mass transit research domain, simultaneous solutions of a depot location problem with other decision problems has reference to rolling stock circulation, e.g. for railway rapid transit system [3].

Concluding, MTCL and VDL are decision problems, which are considered and solved separately, or possibly in combination with other decision problems; however, a simultaneous consideration of both of them has not been extensively discussed up to now, except the previous research of the authors of this paper [13, 14].

1.4. Objective of the research

The research presented in this paper deals with the study on the impact of long-term changes in travel demand while solving mixed the MTLC&VDL decision problem. The authors have conducted a series of computational experiments, as a function of travel demand changes in a long-term planning horizon, and the result of the MTLC&VDL decision problem has been analysed. Travel demand changes are iteratively changed and each change is characterised by a different scenario.

The concept of the research applied in this paper is schematically shown in Fig. 2. Steps 1–6 are referred to the methodology defined in the previous research [14], see Fig. 1.

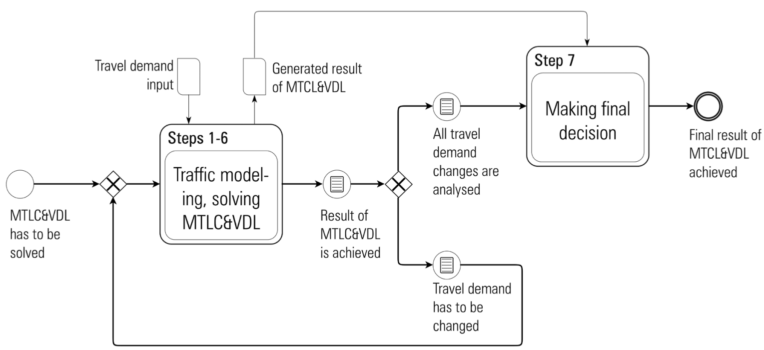

Fig. 2. The methodology of solving mixed MTLC & VDL decision problem as a function of a long-term travel demand changes

2. Computational results

2.1. Key assumptions and parameters

All the computations performed in this paper constitute a further step of the previous research [13, 14]. Thus, some methodological assumptions result from earlier findings, others are related to subsequent methodological steps. Based on the result of previous research, the key assumptions are as follows:

- the objective function, i.e. minimised cost function C, and the set of corresponding constraints are the same [13],
- the generation of a set of i-th lines on the graph of the transport network $G = <j, k>$, is conducted with the application of the ZLT1 algorithm [13], i.e. opposite nodes (located on the border of the considered area) of the transport network are joined with the i-th line,

- a fleet is homogenous, i.e. the same capacity for each vehicle in the fleet is applied; $q_i = 105$ [pas.],
- the passenger comfort factor is assumed and constant; $\lambda_i = 0.75$ [-],
- one out of six alternative locations for vehicle's depot ($l = 1, 2, \ldots, 6$) is looked at; their alternative locations are the same and presented in Fig. 3,
- the computation is performed on the basis of a testing model of a transport network, typical for a city inhabited by around 60,000 inhabitants and covering an area of 47 km^2; the picture of the considered transport network is presented in Fig. 3.

With respect to the objective of this paper, the authors have defined the following additional assumptions:

- traffic analysis zones in the considered area (its number, structure and location) are unchangeable during analysis; there are 13 zones (including 4 zones representing external traffic) and their location is presented in Fig. 3,
- travel demand changes result from two key factors, including *i*) inhabitant's migration from the city centre to the peripheries, and *ii*) increased population number in the considered area,
- different time horizon perspectives are analysed, incl. current state – 1 perspective, and long term – 2 perspectives.

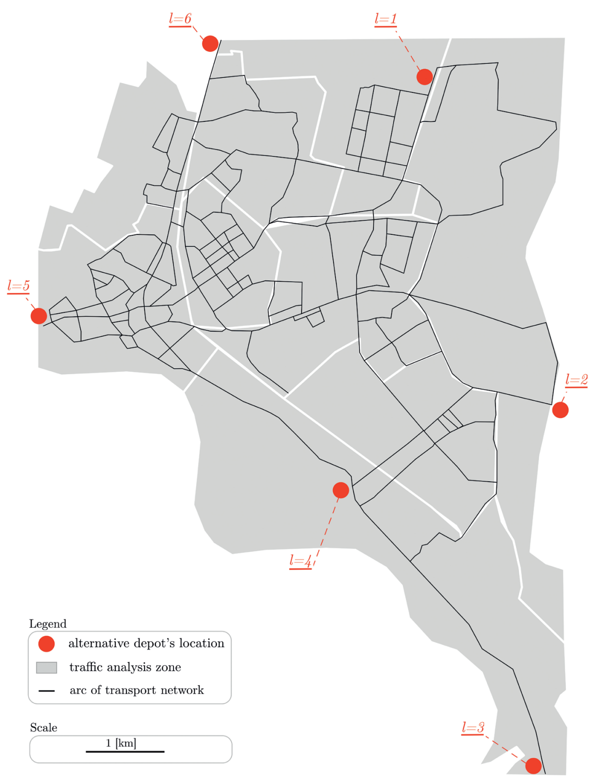

Fig. 3. A general picture of the considered area

2.2. Experiments

All computations based on a schema presented in previous sections, see Fig. 1 and Fig. 2, have been iteratively repeated 3 times for each specific scenario. Scenario 1 (S1) is a representation of the current state of travel demand, and the mixed decision problem of MTLC&VDL is solved. With a scenario 2 (S2), 5% increased explanatory variables (such as the number of inhabitants, employees, students etc.) used to calculate trip generation have been faced, and a considered mixed decision problem is solved again. The decision problem is solved again within scenario 3 (S3), where the same explanatory variables are increased by 10%, compared to S1.

A draft traffic allocation to arcs on the considered transport network is presented in Tab. 1. It consists of the results of analysis in scenario S1, S2 and S3. The representation of the final traffic assignment for a rush hour (7 am–8 am), after modal split operation, as well as the length of each link d_{jk}, are presented in Tab. 2, for scenarios S1, S2 and S3 as well.

Table 1. A draft traffic allocation to arcs of the network for 24 hours

Nodes		Traffic volumes [pas./24h]						Velocity [km/h]						d_{jk} [km]
		P_{jkt}			P_{kjt}			v_{jk}			v_{kj}			
j	*k*	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	
1	6	1769	1821	1886	1290	1326	1362	35	35	35	35	35	35	.80
1	115	1356	1404	1473	1845	1923	1995	45	45	45	45	45	45	.58
4	137	1511	1519	1532	2043	2053	2071	35	35	35	35	35	35	1.21
10	11	3840	3918	3998	3710	3811	3915	60	60	60	60	60	60	.47
11	118	3195	3248	3309	3252	3334	3414	60	60	60	60	60	60	.13
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
138	149	3801	3782	3769	5009	5024	5041	60	60	60	60	60	60	.74
143	144	1470	1449	1424	1043	1040	1053	45	45	45	45	45	45	.46
144	32	1470	1449	1424	1043	1040	1053	35	35	35	35	35	35	.61
161	162	2558	2664	2777	2147	2229	2311	35	35	35	35	35	35	.26
162	31	2965	3085	3206	2509	2603	2700	35	35	35	35	35	35	.20

Since the possibility of presenting a complete list of traffic volumes is limited in this paper, a comparison of passenger traffic volume profiles for each scenario is shown in Fig. 4a. Additionally, a comparison of passenger traffic volume differences between scenarios, i.e. S2-S1 and S3-S1, is presented in Fig. 4b.

While comparing the passenger traffic volumes at individual arcs of the transport network (see Fig. 4b), i.e. scenarios S2-S1 (red line, demand increased by 5%) and S3-S1 (green line, demand increased by 10%), significantly higher differences are observed in the first case. The range of differences for S2-S1 is (-61, 106) [pas./h], and its profile across the transport network is noticeably concentrated around selected arcs of the network. In the case of S3-S1, the differences are in the range (-59, 66) [pas./h], and their profile is relatively equally distributed over the network.

Table 2. A traffic allocation to arcs of the network for rush hours (7am-8am), mass transit only

Nodes		Traffic volumes [pas./h]						Velocity [km/h]						d_{jk} [km]
		P_{jkt}			P_{kjt}			v_{jk}			v_{kj}			
j	*k*	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	
1	6	42	140	83	40	62	70	34	33	33	35	33	34	.80
1	115	40	62	70	42	140	83	45	44	45	45	44	44	.58
4	137	103	83	91	96	113	113	33	33	32	31	30	30	1.21
10	11	59	50	58	91	66	97	55	54	54	54	54	53	.47
11	118	58	50	58	67	66	69	59	59	59	58	58	57	.13
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
138	149	102	80	53	132	77	73	59	59	58	58	56	56	.74
143	144	156	156	160	145	133	157	45	45	45	45	45	45	.46
144	32	156	156	160	145	133	157	35	35	35	35	35	35	.61
161	162	113	171	106	99	107	87	27	27	25	30	26	28	.26
162	31	113	171	106	99	107	87	27	27	25	30	26	28	.20

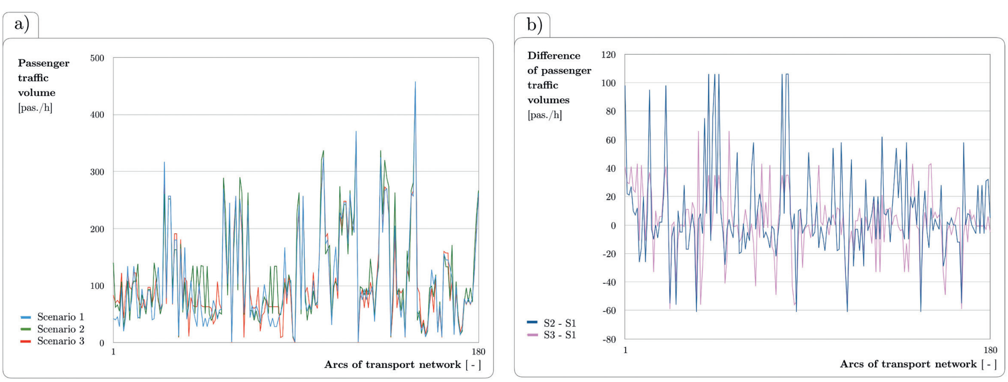

Fig. 4. The scenario-based profile of passenger traffic volume allocated to the arcs of transport network: a) the volumes, b) difference between scenarios

2.3. Discussion of the results

All the computations have been performed using the PTV Visum software (for the traffic modelling part) and Solver Premium Platform (for optimisation part), using LP simplex solver for discrete optimisation. The results obtained under individual scenarios: S1, S2 and S3, are summarised in Tab. 3. They indicate the following key observations:

- in each case, 8 transport lines are defined for the mass transit system, and the common set for all considered scenarios (S1, S2 and S3) is composed of 5 lines, i.e. {5, 7, 11, 12, 21};
- the increased number of the homogenous fleet of vehicles (from 8 vehicles at S1 and S2 to 9 vehicles at S3) results from increased travel demand;
- the total number of 12 courses during rush hour (7 am–8 am) are performed in each scenario;
- one location of the vehicle's depot is suggested for each scenario (a'priori assumed), however, the location at S1 and S2 (l = 6) is different than S3 (l = 5);
- along with the increase of traffic volume over different time horizons (S1, S2 and S3 respectively), and locations of vehicle's depot, the total transport cost is increased too; the value varies from 1,243 to 1,360 [zł/h], depending on scenarios.

Table 3. Scenario-based final results of MTLC&VDL mixed decision problem

Results		Scenarios		
Name	**Unit**	**S1**	**S2**	**S3**
Total number of lines	[items]	8	8	8
Line's numbers*	[-]	{3, *5*, *7*, *11*, *12*, 17, 18, *21*}	{3, *5*, *7*, 10, *11*, *12*, 18, *21*}	{*5*, *7*, 10, *11*, *12*, 15, 17, *21*}
Fleet size	[veh.]	8	8	9
Courses	[items/h]	12	12	12
Depot location (*l*=)	[-]	6	6	5
Objective function *C*	[zł/h]	1,243.0	1,246.9	1,360.1

* line's numbers written by italic are common set for scenarios S1, S2 and S3

3. Conclusions

3.1. Research findings

In the paper, the mixed mass transit line construction and vehicles' depots location decision problem (MTLC&VDL) has been considered. The research presented in this paper has been carried out based on extensive research methodology that is a consecutive step of the work previously undertaken by its authors [13, 14].

The extension of the research is a scenario-based and iteratively repeated solving of the decision problem. Each considered scenario, incl., S1, S2 and S3, has been characterised by a different time horizon (S1 is a current state, S2 and S3 are long-term horizons), and diversified travel demand (S1 – current demand, S2 and S3 – demand increased by 5 and 10% with reference to S1, respectively). As a result of the performed computations, several methodological conclusions have been formulated.

Planning the structure of transport lines, together with the location of the depots for serving the fleet operated on those lines, traffic modelling with anticipated long-term travel demand changes should be performed. Thanks to this, it is possible to determine a resilient solution in the scope of: structure of the lines and corresponding frequency, fleet size, and location of the depot. It also can be stated that the performed calculations have proved a high sensitivity of the mixed MTLC&VDL decision problem of changing the decision situation.

3.2. Further research

Further research related to the mixed MTLC & VDL decision problem will be conducted bi-directionally. On the one hand, research will be carried out related to the evaluation of the simultaneously changed travel demand and supply as well (including, the redefined key parameters of transport infrastructure). On the other hand, it is planned to develop research towards linking the mixed MTLC & VDL decision problem with another separate decision problem, i.e. fleet composition. Thanks to the simultaneously solved, new mixed decision problem of this type, it will be possible to determine the degree of fleet differentiation, which will be adjusted to the changing travel demand in the considered area.

Acknowledgments

The research presented in the paper has been partly funded by the Ministry of Science and Higher Education, Republic of Poland (grant no. 05/51/DSPB/3524). The support is gratefully acknowledged.

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If you want to quote this article, its proper bibliographic entry is as follow: Piotr Sawicki, Szymon Fierek, *The impact of long-term travel demand changes on mixed problems of mass transit lines construction and vehicles' depots location*, Technical Transactions, Vol. 6/2018, pp. 103-112.