Multi-Objective Stop Location Optimisation Model for Minimising Social, User, and Operator Costs in Urban Tram Systems

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ABSTRACT

The relocation of stops can enhance the quality of a transit system, leading to increased usage of sustainable transport modes and thus helping to achieve the sustainability goals of a particular region. Nevertheless, determining optimal stop locations is a relatively intricate task. It involves striking a balance between two competing goals of accessibility and efficiency. Previous research has mainly focused on examining stop relocations on specific line segments using optimisation models. However, these models often make crucial assumptions, particularly regarding transit demand, thereby limiting their applicability.

In this paper a multi-objective optimisation model is presented to make the trade-offs between several factors influencing stop locations explicit. Detailed socio-economic data of zones is used in the model, alongside current travel behaviour, to estimate transit demand precisely. Additionally, the effects of stop relocation on operations are estimated using running time data. As a result, optimal stop locations for an entire transit system can be determined.

The results of a case study of the tram system of The Hague indicate that in areas where trip distances are short and near the end of a tram line, stop spacing should be denser compared to other parts of the system. Moreover, it is concluded that stops are not always optimal where two transit lines intersect. Only in case of a high share of transfer passengers, a stop should be located irrespective of the other factors. Finally, it is concluded that the potential speed on a line section does not affect the optimal stop spacing significantly.

Keywords: Stop Spacing, Stop Location, Multi-Objective Optimisation Model, Transit Network Design, Tram

1 INTRODUCTION

The improvement of public transit is seen as an increasingly important solution to the high costs of congestion, traffic accidents and the escalating environmental impacts of car-centric transportation systems observed in numerous cities today (1,2, 3). Stop spacing is a key design variable in urban public transport planning which can improve the efficiency of transport networks (4). Over the past decades, numerous studies have examined the generalised costs of relevant stakeholders to determine the optimal stop spacing of a transit network (5-7). Researchers analysed the access and egress times, the in-vehicle times, the operator costs and some researchers also included external costs in the computation of social welfare (8-10).

Several studies have emphasised the importance of modelling the travel demand along a transit corridor with greater precision and of improving the accuracy of computing running times and energy consumption (11,12). Particularly in demand estimation significant improvements can be achieved, as many existing studies often assume an even distribution of demand along a corridor or assume a gradually decreasing demand the further a stop is from the city centre (13-15). Current guidelines depend on these assumptions, and therefore optimal stop locations cannot be established.

It is found in the literature that sociodemographic characteristics, land uses and building densities highly affect transit demand (16). Moreover, the local street network has a large influence on the access and egress distances and the determination of optimal stop locations (17). The access and egress time of passengers is influenced by people's speed as well, which depends on the sociodemographic characteristics and the used access or egress mode (18). However, limited papers consider the variations in access and egress speed between passengers (19). It is furthermore concluded that people accept larger access and egress distances if a transit line offers better connectivity, speed and reliability (20,21). Besides, it is essential to incorporate the transfer walking times between stops to capture the full user costs. When considering a network, stops on different lines can affect where passengers transfer (22).

In general, with fewer stops transit becomes quicker over a route (7). Therefore, the in-vehicle times differ when stop locations change. However, the local speed and the stop usage also highly effect the possible time saving (23,24). Detailed data on vehicle characteristics, infrastructure and the environment must be obtained to precisely estimate running times (8,25). Additionally, the energy saving by the removal of a stop location can be different across a system, therefore these aspects require an appropriate model to compute the operational costs for any given alternative (26). Finally, limited research is conducted on the external costs of transit operations. The most mentioned external costs are the emission costs (26). These emission costs will also be considered in this study, while other external costs are outside the scope of the research.

All considered time and cost components are weighted and compared in a model to determine the optimal configuration of stops for the chosen objective. In this paper the development of a multi-objective model for optimising stop locations within an urban tram network is described. The model considers multiple relevant transit objectives such as the minimisation of social, user and operator costs. By combining and refining best practices from existing optimisation models, this study has developed a stop location model that can be applied to a diverse range of scenarios. The model offers valuable insights into the crucial interplay between stop locations, usage patterns, and operational considerations.

In Chapter 2, the methodology is covered and the setup of the stop optimisation model is presented. Next, in Chapter 3 a case study is introduced and the model is applied on this case study. The results of the model are also presented in this chapter. Finally, a discussion of the model and the results is given in Chapter 4, together with the conclusions of this paper.

2 METHODOLOGY

To be able to precisely determine optimal stop locations over a transit system, a stop optimisation model is developed. The various cost components of all possible stop configurations in a network are determined in this model and, with the use of a solving algorithm, the optimal network for the chosen objective can be obtained. Besides, preprocessing steps are undertaken to reduce the computation effort of the main model.

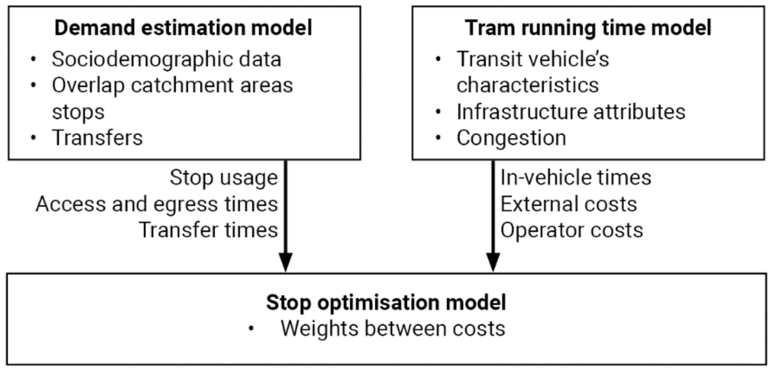

FIGURE 1 Outline of the models used for determining optimal stop locations.

As is visualised in **Figure 1**, a *demand estimation model* is developed to determine the demand at a specific stop location while considering land uses, building densities, and sociodemographic characteristics of the areas around a stop. The proximity of nearby stops is also considered, as closely spaced stops compete for ridership. Consequently, city blocks are created and all demand of individual blocks is allocated to the closest stop locations. By utilising current stop usage data, the model derives relevant demand parameters. Subsequently, the demand at each potential stop location is determined and the average access and egress distances to different blocks are calculated for different stop configurations. Considering the sociodemographic features of each block, the access and egress times can be computed as well. Transfer times are also computed for various stop configurations, focusing solely on the walking distance between transfer locations.

Furthermore, the transit vehicle's characteristics, infrastructure attributes, and potential congestion are considered to estimate the *tram running times* between existing stops. These running times can be calibrated with vehicle data to obtain the operational speeds on various parts of the network. Afterward, the time delay due to a vehicle having to accelerate and brake for a potential stop can be computed and this time delay is used as input for the optimisation model. Dwell times can be calculated by considering the demand at a stop. Current stop usage and boarding time data are applied to calibrate the model as well. Besides, the same procedures are performed for the calculation of the energy consumption for different stop locations. This energy consumption is not only important to determine operator costs, but also for the calculation of the social costs (i.e., emission costs).

Afterward, the output of these sub-modules is used by the main *stop optimisation model* which determines the optimal stop locations, while considering specific weights between time and cost components for the chosen objective. Three objectives are examined in total, whereby the first objective is the minimisation of the social costs. The second and third objectives are the minimisation of user costs and operator costs, respectively. The social costs are the sum of the user costs, operator costs and external costs. However, simply minimising the total social costs in an optimisation model would lead to an undesirable solution containing a network with no stops. In this case there are no passengers, no travel time, and thus no user costs. Additionally, the operator costs and external costs are minimised when no stops are chosen. In other stop optimisation models this would not be applicable as the number of passengers taking transit is considered constant (27), or accessibility constraint are applied (28), while in the model presented in this paper both are not the case.

To still be able to find the optimal stop locations with varying demand, another method is implemented. Namely, the objective function of the model incorporates the percentual difference in users costs with respect to the user costs in the current network. The user costs should only decrease in the case that the percentual decrease in ridership and in passenger kilometres is less. This would imply that the average user costs drop, thus being an improved solution. Operator costs and external costs are incorporated as usual, whereby fewer costs lead to an improved solution. The mathematical notation of the objective function that is used to minimise social costs is given in **Equation 1**:

$$Obj(\text{min}) = C_{U_{current}} * \left(\frac{C_U}{C_{U_{current}}} - \frac{B}{B_{current}} - \frac{KM}{KM_{current}}\right) + C_O + C_E \qquad (1)$$

where:

C_U:	Total user costs in tram network
$C_{U_{Current}}$:	Total user costs in current tram network
B:	Total number of boardings in tram network
$B_{Current}$:	Total number of boardings in current tram network
KM:	Total number of passenger kilometres in tram network
$KM_{Current}$:	Total number of passenger kilometres in current tram network
C_O:	Total operator costs in tram network
C_E:	Total external costs in tram network

The second objective is the minimisation of user costs. For this objective, a similar objective function is used. The operator costs and external costs are disregarded, thus the best trade-off between various travel time components as a result of stop locations is determined. The used formulation is presented in **Equation 2**:

$$Obj(\text{min}) = C_{U_{current}} * \left(\frac{C_U}{C_{U_{current}}} - \frac{B}{B_{current}} - \frac{KM}{KM_{current}}\right) \qquad (2)$$

Contrary, for the third objective, the minimisation of the operator costs, a different set-up of the objective function is used. Minimisation of costs can be achieved with either significantly more passengers, or with reduced operational costs, whereby the revenue for the operator is heavily dependent on the used pricing scheme. For the considered network, the average revenue per boarding and average revenue per passenger kilometre should be obtained. These can be obtained using data on total ticket sales, total passengers, and passenger kilometres in the system. Subsequently, the objective function in the optimisation model to find the optimal network which minimises operator costs should be the following, as presented in **Equation 3**:

$$Obj(\text{min}) = -f_b * B - f_{km} * KM + C_O \qquad (3)$$

where:

f_b:	Average boarding fare
f_{km}:	Average kilometre fare

Moreover, constraints are imposed in the optimisation model to restrict the search for solutions to those that are realistic and feasible. For instance, it is assumed that on a shared section of track all lines stop at the same locations. Hence, with constraints it should be ensured that stop configurations which do not adhere to this are not within the solution space of the model. The formulation of the constraints is done using linear programming, similarly to the formulation of the objective functions, to increase the computational efficiency of the model.

The major constraints used in the model are the balancing of the number of passengers boarding and alighting on a transit line in a particular direction. When this balancing for a particular stop configuration is achieved, the user costs, operator costs, and emission costs can be computed. For example, when the ridership at a stop location is known, dwell times and total running times can be calculated. Subsequently, the number of passengers on a section can be multiplied with the travel costs on that segment to obtain in-vehicle user cost. The constraint sets for the determination of the number of passengers boarding and alighting at a specific stop, based on boarding and alighting demand, are depicted in **Equations 4 to 18**:

$$Yb_{i,j,z} \leq X_{i,j,z} * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (4)$$

$$Yb_{i,j,z} \geq X_{i,j,z} * -M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (5)$$

$$Yb_{i,j,z} \leq bd_{i,j,z} * Pb_i + \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (6)$$

$$Yb_{i,j,z} \leq bd_{i,j,z} * Pb_i - \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (7)$$

$$B_{i,j} = \sum_{\boldsymbol{z} \in \mathbf{Z}_{i,j}} Yb_{i,j,z} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad (8)$$

$$Ya_{i,j,z} \leq X_{i,j,z} * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (9)$$

$$Ya_{i,j,z} \geq X_{i,j,z} * -M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (10)$$

$$Ya_{i,j,z} \leq ad_{i,j,z} * Pa_i + \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (11)$$

$$Ya_{i,j,z} \geq ad_{i,j,z} * Pa_i - \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (12)$$

$$A_{i,j} = \sum_{\boldsymbol{z} \in \mathbf{Z}_{i,j}} Ya_{i,j,z} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad (13)$$

$$Pb_i \leq 1 + (1 - Pa_i) + (1 - ya_i) * \mathrm{M} \qquad \forall i \in \boldsymbol{L} \qquad (14)$$

$$Pa_i \leq 1 + (1 - Pb_i) + (1 - yb_i) * \mathrm{M} \qquad \forall i \in \boldsymbol{L} \qquad (15)$$

$$yb_i + ya_i \leq 1 \qquad \forall i \in \boldsymbol{L} \qquad (16)$$

$$0.5 \leq Pb_i \leq 2 \qquad \forall i \in \boldsymbol{L} \qquad (17)$$

$$0.5 \leq Pa_i \leq 2 \qquad \forall i \in \boldsymbol{L} \qquad (18)$$

where:

$Yb_{i,j,z}$: Continuous dummy variable indicating the boarding demand at stop j on line i if stop set $\boldsymbol{z}$ is chosen
$Ya_{i,j,z}$: Continuous dummy variable indicating the alighting demand at stop j on line i if stop set $\boldsymbol{z}$ is chosen
$X_{i,j,z}$: Dummy variable for stop j on line i indicating if stop set $\boldsymbol{z}$ is chosen
M: Sufficiently large fictious constant
$\mathbf{S_i}$: Set of potential stops for line i
$\boldsymbol{L}$: Set of lines in the network
$\mathbf{Z}_{\boldsymbol{i,j}}$: Possible stop sets around stop j on line i
$\boldsymbol{Z}$: All possible stop sets for all stops
$\mathrm{bd}_{i,j,z}$: Boarding demand at stop j on line i when stop set $\boldsymbol{z}$ is chosen
$\mathrm{ad}_{i,j,z}$: Alighting demand at stop j on line i when stop set $\boldsymbol{z}$ is chosen
Pb_i: Boarding balancing factor for line i
Pa_i: Alighting balancing factor for line i
B_i: Total number of boardings on line i
A_i: Total number of alightings on line i
yb_i: Dummy variable for the boarding balancing factor of line i
ya_i: Dummy variable for the alighting balancing factor of line i

What is shown is that in order to retain a linear problem, the model requires multiple constraints with dummy variables, where normally only a single constraint set is used. For the determination of, for instance, operator costs, the same dummy variables should be applied together with several constraints. Additionally, with **Equations 19 to 21** it is assured that exactly one configuration of stops is chosen within a specific area. The optimisation model can then determine the optimal stop configuration with the lowest objective value:

$$X_{i,j,z} \leq 1 - x_{i,j} \qquad \forall i,j \in \boldsymbol{z_1}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (19)$$

$$X_{i,j,z} \leq x_{i,j} \qquad \forall i,j \in \boldsymbol{z_0}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (20)$$

$$X_{i,j,z} \geq \sum_{i,j \in \boldsymbol{z}} x_{i,j} \qquad \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (21)$$

where:

$x_{i,j}$:	Binary variable indicating if stop j on line i is chosen
$\mathbf{z_1}$:	Possible stop set around stop j on line i
$\mathbf{z_0}$:	Set of stops which are not chosen in stop set $\boldsymbol{z}$

For a more detailed description of the constraints and the mathematical formulation of all other constraints, the research is referred to (29).

Lastly, the model is run in iterations to incorporate the effects of shorter journey times on overall transit demand. If the generalised travel times on a line section drop, in the next iteration the demand on that line section is increased. This procedure is repeated till the stop locations in the network do not change anymore between iterations. The changes in demand per line section are computed using the travel cost elasticity as exhibited in **Equation 22** below:

$$E = \frac{\Delta Q}{\Delta T} * \frac{T}{Q} \qquad (22)$$

where:

E:	Travel cost elasticity of demand
Q:	Original transit demand
ΔQ:	Change in transit demand
T:	Original travel time costs
ΔT:	Change in travel time costs

At last, final optimal stop locations are obtained and important output metrics are analysed.

3 APPLICATION

To demonstrate the optimisation model and to find the optimal stop locations in the tram network of The Hague, a case study is performed.

Case Study Description and Implementation

The tram network in The Hague, the Netherlands served as a case study. The examined network consists of 13 tram lines which connect The Hague to neighbouring municipalities, carrying on average 275,000 passengers daily. In total, almost 900,000 residents live in the service area of the tram system. Besides, all tram routes are being operated by HTM Personenvervoer N.V., the urban transit operator of The Hague. They run most tram routes every 10 to 15 minutes, with frequencies of up to 34 trams per hour at peak times on sections shared between lines.

The tram network is highly interconnected with the bus network, but the bus stops are not optimised in the stop optimisation model to reduce the required computational effort. Therefore, it assumed that these stop locations remain unchanged. Nonetheless, the passengers transferring from tram vehicles to other transit lines are considered in the model.

In the case study, data from smartcards and automatic vehicle location (AVL) systems are utilised. The smartcard data consists of tap-in and tap-out records from the months of July 2019 and November 2019 (30). Two months with distinctive travel behaviour are used to investigate if optimal stop locations are different throughout the year. For each month, stop usage is analysed based on an average day of the week, allowing for the computation of average weekly ridership. Similarly, running time data is examined and averages are computed, with the upper and lower quartiles being excluded from the analysis. AVL-data provides information on the departure and arrival times at each stop, enabling the calculation of running times and dwell times (31). Additionally, socio-economic data from Statistics Netherlands (32) are incorporated to extract essential information regarding population density and land usage in specific areas of the city.

Case Study Results

The findings from the case study, presented in **Table 1**, reveal that applying different transit objectives results in varying outcomes for the optimal network configuration. When the objective considered is minimising user costs, the highest increase in ridership is observed. The system experiences approximately a 4% rise in the number of passengers, along with an 8% increase in total passenger kilometres travelled. Moreover, this objective leads to a reduction of around 3% in operator costs. Minimising social costs or operator costs yields less growth in the number of passengers but generates significant savings in operational expenses. The estimated increase in passenger numbers for these objectives is approximately 1%, while transit agency costs see a potential reduction of 9%. A government, transit agency or operator should therefore carefully consider the objective for which a transit system is optimised.

TABLE 1 Key Performance Indicators for the Three Considered Model Objectives

	Optimal for society	Optimal for the user	Optimal for the operator
Number of stops	-16.5%	-5.7%	-16.5%
Ridership	+0.8%	+3.5%	+1.2%
Passenger kilometres	+6.2%	+7.7%	+7.7%
Average access and egress time	+1.5%	+2.0%	+1.8%
Average in-vehicle time	-2.6%	+1.6%	-0.4%
Average transfer walking time	+27.9%	-4.6%	+19.7%
Operator costs	-8.6%	-3.2%	-8.8%
Rolling stock required	-6.3%	-1.9%	-6.3%
Energy consumption	-13.7%	-5.9%	-14.4%
Emission costs	-13.7%	-5.9%	-14.4%

Across all considered objectives, the optimal network features a reduced number of stops compared to the current network. As is shown in Table 1, the user-oriented optimal network has 5.7% fewer stops, while the operator and societal optimal networks see a reduction of 16.5% in the number of stops. As can be expected, this results in longer average access and egress times but shorter in-vehicle times, as well as reduced operational costs. Nevertheless, fewer stops do not result in fewer passengers, as with the quicker average trip times the tram becomes more attractive to use. Additionally, unless the system is optimised for the user, average transfer walking times increase significantly. In numerous cases, the advantages of improving the spacing between tram stops outweigh the importance of minimising transfer walking distances. However, despite the decrease in the overall number of tram stops, the optimal network with the lowest social costs results in only about 0.5% of homes in the metropolitan region losing a transit stop within 500 metres.

Furthermore, due to the increased service speeds in the network, less drivers and vehicles are required for operation if the frequencies remain the same. Besides, there is a decrease in the overall energy consumption of vehicles in the system due to the fewer stops. Thus, both the operator costs and emission costs drop for all considered objectives.

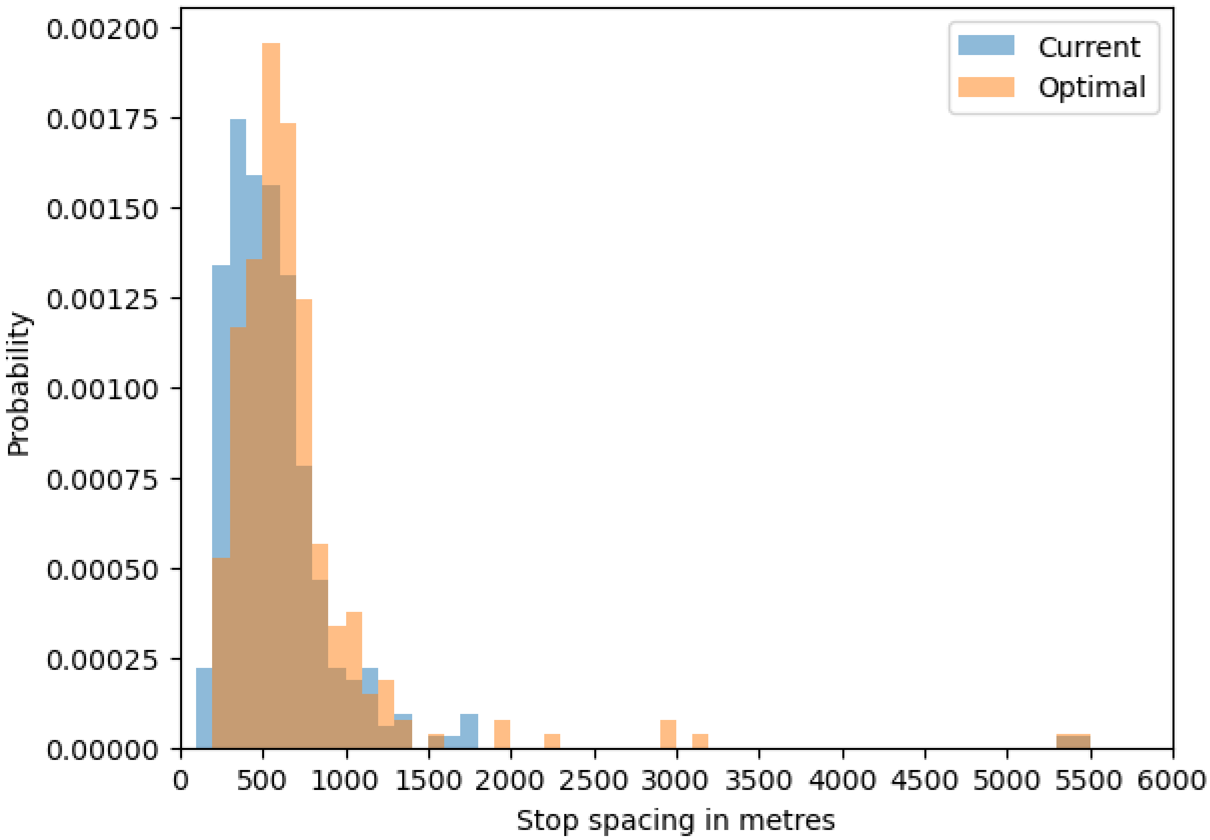

FIGURE 2 Distribution of stop spacing in current network of The Hague and the optimal network with the lowest social costs.

As is visualised in **Figure 2**, optimal stop spacing varies across the network of The Hague, with most stops being optimally placed if they are 300 m to 800 m apart when the social costs are minimised. As optimal stop spacing varies over the network, there are both areas where stops should be removed, as well as areas where the number of stops should increase. For both instances, an example is encircled in **Figure 3**. Furthermore, it is found that the ratio between the demand on a section and the number of through passengers is the major factor indicating what optimal stop spacing should be, as visualised in **Figure 4**. As this ratio increases stop spacing should be denser, while for lower values fewer stops should be placed. Although there is still quite some deviation from the orange trend line, it can be noted that there is a lower limit on what optimal stop spacing should be, indicated with the red lines in the figure. For higher percentages of boardings over through passengers, the lower limit on optimal stop spacing is approximately 300 metres, while for lower percentages this minimum stop spacing can be as high as 800 metres. Nonetheless, the deviations in the figure are mainly the result of the demand not being constant across every kilometre and, for instance, the street network constraining stops to be placed an optimal distance apart.

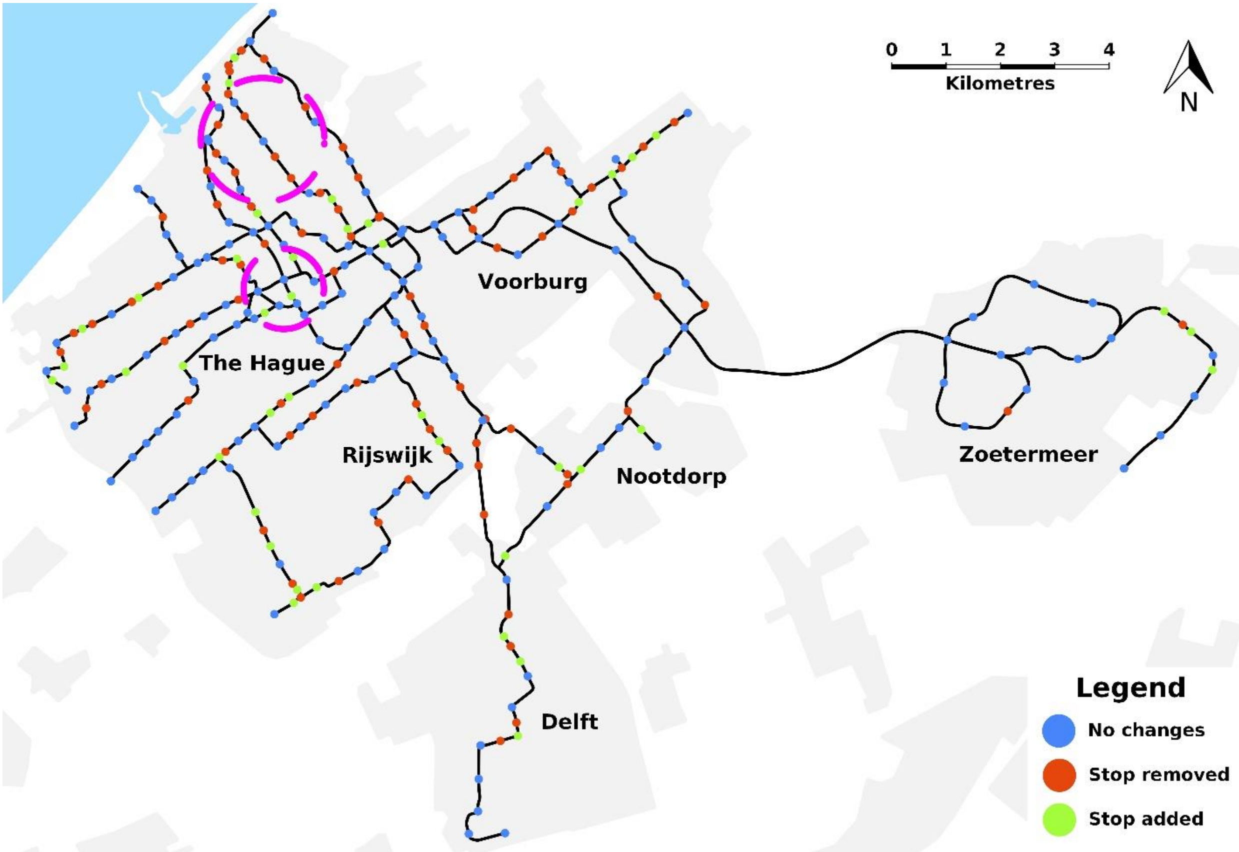

FIGURE 3 Optimal stop locations with the lowest social costs for the tram network of The Hague.

Typically, in areas with shorter trips, and near the beginning and end of a tram line, the ideal spacing falls between 300 m and 500 m. However, in other urban areas optimal spacing is around 500 m to 800 m. Additionally, for parts of the network where trams are used for longer trips, like suburban lines, average stop spacing of more than 800 m is generally optimal. Finally, if the demand for a kilometre of tram line is only 10% of the through passengers, placing a stop is not optimal, which may be the case in low-density areas. With regards to The Hague, businesses in the catchment area and the income of households are the main predictors of the transit demand. Businesses up to 800 m from a stop are significant predictors and households up to 1.6 km are significant.

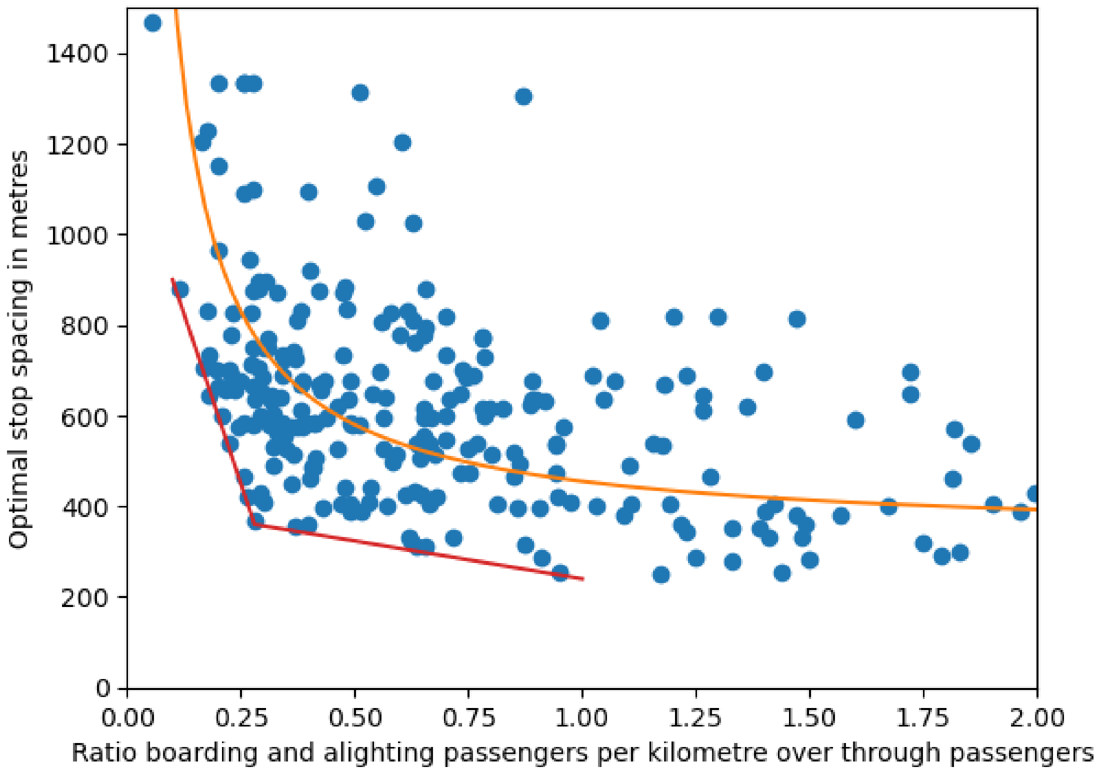

FIGURE 4 Relation between demand per kilometre, through passengers and stop spacing across the network of The Hague with the lowest social costs. The trend line is indicated in orange, whilst the lower limits of optimal stop spacing are depicted in red.

Moreover, factors such as local demand and the street network must be considered when determining optimal stop placement. Transfer passengers are also a form of local demand, but it is concluded that it is not always necessary to place a stop at every transfer location. A stop should only be added definitively if at least 10% of total passengers in a vehicle transfer to another line at that specific spot. As is concluded from a sensitivity analysis, this percentage can be slightly higher or lower depending on the chosen parameters (29). Nevertheless, from the sensitivity analysis it is concluded that transfer walking times only have a limited effect on the optimal stop locations in the network of The Hague. Similarly, altering the access and egress speeds by bicycle or emissions costs does not lead to different optimal solutions. It is also concluded that the optimal stop locations do not change drastically when the model is calibrated with either demand form July 2019 or November 2019. The optimal network with the lowest social costs is mostly influenced by the value of time of passengers and the energy costs (29). Within the ranges tested for these parameters, the optimal number of stops is increased or decreased by around 4%.

Finally, running speeds do not influence optimal stop spacing significantly in the network of The Hague, as is seen in **Figure 5**. One possible reason why speeds are not significant in the tram system of The Hague is the fact that dwell times are relatively long. For the less used stops it takes on average 20 seconds to let all people in and out at a stop and this can increase to up to 50 seconds for the busiest stops. Contrary, only 4 to 24 seconds are lost due to a tram having to brake and accelerate for a stop, whereby in most areas of the city this time loss is only 7 seconds.

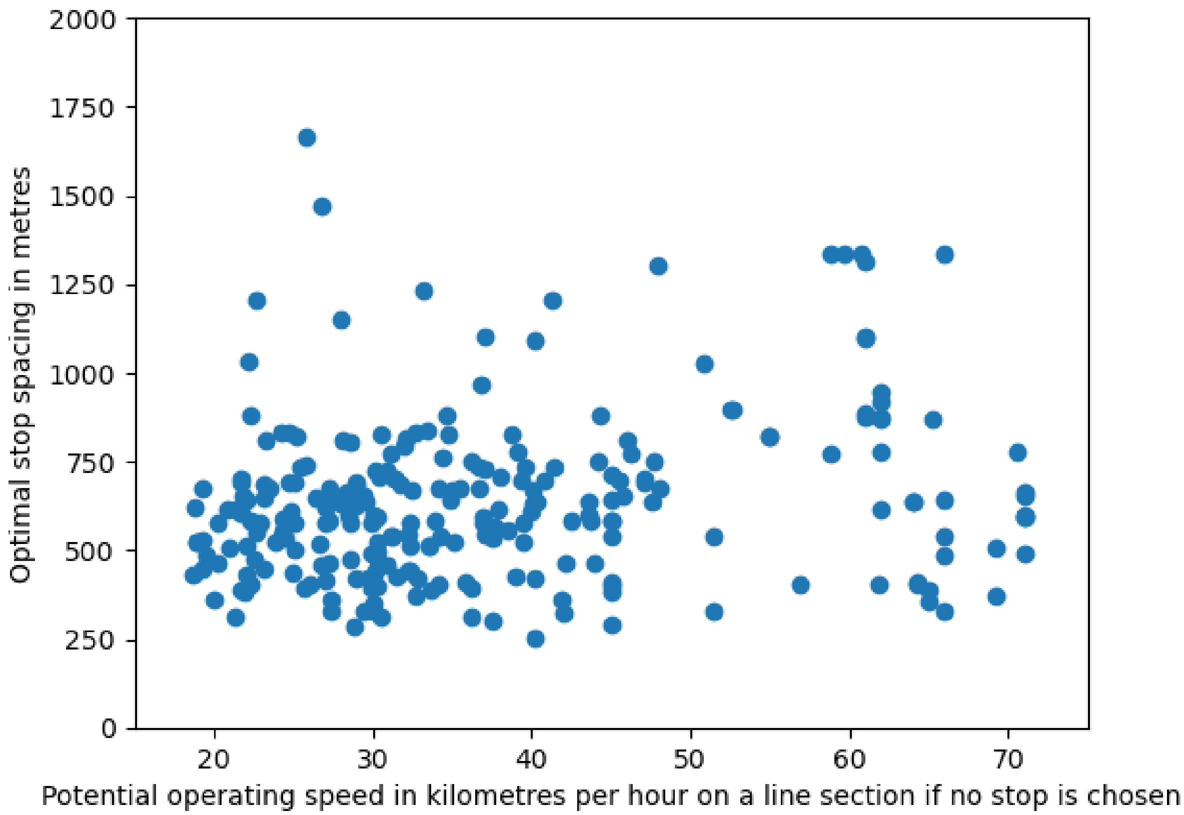

FIGURE 5 Relation between the potential operating speed on a line section and the optimal stop spacing in The Hague when social costs are minimised.

4 DISCUSSION AND CONCLUSION

This paper details the development of a multi-objective model for optimising stop locations within an urban tram network while considering multiple transit objectives. The model provides valuable insights into the key interactions between stop locations, usage, and operations. The model presented in this study addresses the gap in literature by integrating a comprehensive assessment of alternatives, considering network effects, and providing a thorough analysis of demand at various stop locations and travel times between them. Additionally, the results demonstrate the potential for increasing ridership while achieving operational cost savings. In the case of The Hague, operational costs savings of up to 9% can be achieved without any negative influence on the ridership.

Most importantly, it is concluded that in areas where trip distances are short and near the end of a tram line, stop spacing should be denser, compared to other sections in the system. This is in line with previous findings (14,27). Hence, it is recommended that in the planning of stop locations, the travel behaviour should be properly investigated. However, the conclusions from the case study that stops are not always optimal where transit lines intersect conflicts with previous studies (5,19). Also, the conclusion that the potential speed on a line section does not affect optimal stop distance significantly, is not commonly agreed upon (21,33,34). Nevertheless, average trip lengths are possibly dependent on running times and therefore track speeds. Thus, optimal stop distances and track speeds are indirectly dependent on each other.

Still, assumptions have been made, mainly on the demand side, which could affect the results and the usability of the model. Most importantly, it was assumed that transit riders would not change their itinerary with varying stop locations and the increased demand due to shorter journey times was also approximated. It was furthermore assumed that transit riders access the stop closest to their origin, with papers indicating this is not always the case (35). However, as the properties between transit stops and services in the trams system are not majorly different, it is expected that passengers mostly consider the access and egress time to and from stops in their stop choice. Nonetheless, further research can improve the modelling of transport trips with varying stop locations by incorporating utility functions for mode choice and itinerary choice. This can be best implemented in the iterations of the stop optimisation model.

Additionally, in the model it is assumed that all vehicles halt at all stops along a transit route at all times. Hence, the effects of request stops are not incorporated in the model. To add, the model only considers walking and cycling as access and egress modes and does not investigate the effects of new micromobility solutions and on-demand transit on optimal stop locations. These aspects can be further researched in future studies. The external costs can be further explored in future research as well since only the emission costs were considered in this paper.

The conclusions drawn from the case study conducted in this research can be extended to other transit networks. This paper provides a range for optimal stop spacing and identifies key factors that influence optimal stop locations. The main recommendation for transit planning is to incorporate the travel behaviour into the evaluation process of current transit lines and corresponding stop locations. Depending on the observed travel behaviour, different stop locations are optimal. Besides, it is important to realise that fewer stops do not result in fewer passengers, as quicker overall trip times can increase the attractiveness of a transit network. However, since many factors are relevant, a stop optimisation model remains necessary to determine the exact optimal stop locations across a transit system. The developed stop optimisation model can be applied to other transit networks. Nevertheless, the model parameters require a lot of specific input data from the network being evaluated.

Finally, although the stop optimisation model shows different alternative solutions, it is important to note that the model is not the absolute truth. The relocation of certain stops can, for instance, disproportionally burden certain groups in society which should also be considered. Due to the longer access and egress distances, physically impaired people might be disadvantaged the most. Therefore, the model and its results are part of a wider discussion on the trade-offs between accessibility and efficiency in the transport domain. The model should be treated as an instrument to create understanding in complex systems and assist in transit planning. Nevertheless, by presenting the possible outcomes, the model enables stakeholders to make more informed decisions and engage in meaningful discussions based on evidence and analysis.

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The authors confirm contribution to the paper as follows: study conception and design: T. de Ridder; data collection: T. de Ridder; analysis and interpretation of results: T. de Ridder, J. van der Stok; draft manuscript preparation: T. de Ridder, H. Farah, N. van Oort. All authors reviewed the results and approved the final version of the manuscript.

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