High quality public transport and promotion of non-motorized transport – compromise or complement? An analytical approach assessing conflicts

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Abstract

Public transport is a very efficient way to handle large traffic flows in urban areas. At the same time, and especially in Europe, non-motorized transport is being promoted as a further, environmental friendly and healthy way of urban mobility. This includes the introduction and extension of separate lanes to increase safety and convenience of bikers and pedestrians. However, most cities have limited space for expanding streets and roads which can lead to a conflict between the different uses. It is critical to clearly understand the impacts of these changes on public transport. In this research, a quick assessment model was developed that analyzes the impact of changes to roadway design and policy that can affect public transport services. It was developed for Zurich's public transport operator *Verkehrsbetriebe Zürich* (VBZ) to help them quickly assess changes such as the elimination of separate right-of-ways or the introduction of slow zones and also to help illustrate the impacts of these changes to non-technical audiences. The model uses a series of analytical calculations to analyze the main relationships between key public transport inputs and outputs. It was validated using data from Zurich's tram and bus network. The case studies examine the influence of reducing separate right-of-ways, the expansion of 30 km/h zones and changes to stop distances on public transport operations.

1. INTRODUCTION

No city has enough street space to satisfy everyone. Space on inner city roads is limited and, consequently, not all modes of transport can have their own right-of-way. As multimodal traffic grows, conflicts arise as to which mode should have priority. Zurich has had a long-standing program giving priority to public transport and the city's current mobility strategy [1] [2] considers public transport a backbone of urban mobility. According to this policy, future traffic growth should be handled by efficient, punctual and reliable public transport systems. However, at the same time, the mobility strategy calls for the promotion of non-motorized transport and the expansion of 30 km/h zones. Meeting all these objectives on roads already experiencing congestion is very difficult. Figure 1 illustrates a typical situation in Zurich. Adding separate bike lanes on this roadway would mean reducing sidewalk space or eliminating the separate right-of-way for trams. In short, expanding space for one mode can often only be gained at a reduction of space for other modes. One popular idea for increasing urban livability and encouraging non-motorized transport is the introduction of mixed traffic or shared-space zones. These zones allow scarce space in urban cores to be used by as many actors as possible, including public transport. However, the introduction of shared-space zones creates the risk of reducing public transport reliability and speed, making it less attractive and, at the same time, increasing operating costs.

Figure 1 Major road in Zurich, with available space taken up fully by tram line, automobile lanes and sidewalk [L. Naegeli].

This research developed a model for assessing the impacts of exclusive public transport lanes and shared-space zones on public transport operations. The model was developed for Zurich's public transport operator, *Verkehrsbetriebe Zürich* (VBZ), to help better understand and communicate the impacts of these measures to both transport professionals and those without a public transport background, e.g. decision makers in municipal authorities and political functions. Therefore, the goal was to make it easy to use so that even non-professionals can try out a few inputs on their own.

The model considers the main influences on public transport operations and therefore cannot substitute for detailed transport modeling on the network or corridor level. However, the model does very carefully consider public transport operations at the line level and is sufficient to assess the overall impacts. This paper describes development and application of the model and summarizes results of a case study in Zurich. The case study showed that the model was quite helpful in understanding the impacts of different proposed changes.

2. LITERATURE REVIEW

The public transport impact model developed in this research was designed to show how infrastructure changes (e.g. exclusive lanes, shared space zones) would impact public transport operations. Accordingly, the model had to consider all aspects of operations from stop dwell time to traffic conditions. Given this broad scope, this section summarizes very briefly only the most important literature consulted. The Highway Capacity Manual (HCM) [3], Transit Capacity and Quality of Service Manual (TCQSM) [4] and the German Highway Capacity Manual (HBS) [5] all describe guidelines for evaluating public transport quality and capacity, together with providing key indicators and some influencing factors, mainly between the built infrastructure, traffic volumes, operation regimes and the regularity and capacity of service that can be realized under those circumstances.

Capacity is a quantitatively measurable indicator, which is influenced by many factors in- and outside of the transit system. In the context of public transport, capacity is the maximum number of passengers that can be transported through a certain section in a certain time. This value is theoretically the product of vehicle capacity and frequency, but is influenced by many other factors. Anderhub et al. [6] propose a model for determining actual capacity by applying reducing factors (e.g. buffer times) to a theoretical capacity (vehicle capacity x headways).

Speed is another important measure for public transport quality. For example, speed determines how many vehicles are needed to operate a given line. Speed is determined by many factors such as dwell time, infrastructure and traffic conditions. Each of these is impacted by other considerations, for example ticketing regimes influence dwell time, with proof-of-payment being the most efficient because the driver does not have to spend time on ticket sales and checking and, furthermore, passengers can use all doors for boarding, speeding up the boarding process [7] [8].

Passenger loads also influence dwell time, especially when loads become high enough to impact vehicle boarding and alighting. Weidmann [9] developed a detailed model to estimate boarding and alighting time as a function of load, number of passengers boarding/alighting and vehicle characteristics and e.g. Currie et.al. [8] showed that elevated tram platforms can reduce dwell time by up to 34%.

Public transport speed also depends on the right-of-way. Research has shown that exclusive right-of-way is better than operating in mixed traffic, but the actual speed that can be achieved depends on many specific design features [10] [11].

Orth et.al. developed a framework for evaluating public transport quality based on four indicators: headway adherence, on-time performance, public transport speed relative to automobile speed, and passenger density [12] based on an extensive study of indicator methods and assessment approaches.

Elasticity measures are used to evaluate the impacts of changes on passenger demand. In the context of this research elasticity values from Switzerland were used [13] [14].

In summary, there is an abundance of work considering the individual influences on public transport capacity and quality that can be used in developing an impact evaluation model. Current research (e.g. [15] [16]) focuses on simulation methods. The advantage of such methods is the relatively large number of influences that can be considered, a usually satisfyingly high level of precision and the accounting for some random effects. On the other hand, they require some effort and experience in implementation and calibration.

3. PUBLIC TRANSPORT IMPACT MODEL

The public transport impact model was developed in three steps. First, the factors influencing public transport operations were identified. Second, a qualitative model was developed by analyzing the linkages and relationships between factors, and their impacts on operations. Finally, a quantitative model was created by developing algorithms and processes (in an Excel worksheet) designed to provide output describing the quality of public transport service. Since the model contains too many algorithms and processes to fully describe in this paper, Section 4 describes how the model calculates speed, one of the most important parameters, as an example.

3.1 Public Transport Operations Influence Factors

The first step in developing the model was to identify, through literature review, all the factors that can potentially influence public transport operations. Then, these factors were classified into ten groups. Two classes of factors were excluded from the model: drivers and weather. Drivers were excluded because the behavior of the drivers is difficult to model accurately and because driving styles are largely within control of the public transport operator through e.g. trainings. Weather was excluded because, while weather has a potentially large impact, it is subject to random changes and aside from extreme and rare events such as heavy snowfall, the actual impact is quite limited. Table 1 summarizes the influence factors and their classification.

Class	Influence factor
Vehicles	- acceleration and deceleration - maximum speeds - vehicle capacity (number of seats and standing space) - number and size of doors - seating comfort
Passengers	- accepted standing density - number of passengers per stop - total number of passengers - passenger exchange times
Operation plan	- dwell times - ticketing (on-board, pre-sale,…) - door operation regime (eg., only front door for entrance) - frequency of service - transport speeds (including stops) - travel time - number of vehicles needed - length of line - buffer times - kilometers traveled per vehicle
Infrastructure	- stop type (number of berths, waiting times) - step between vehicle and platform - share of fully separated right-of-way (no intersections, higher speed limits) - separate lane (speed limits as on roads, intersections) - share of mixed traffic zones - curviness and grades (applies especially for tram operations) - speed limits - intersections (number and design) - signal prioritization - turning lanes
Traffic	- traffic volume in mixed traffic zones with cars - traffic volume in mixed traffic zones with non-motorized traffic
Quality and Availability	- service timespan - stop spacing - comfort - passenger information - service quality
Finance	- ticket prices - operating and fixed cost - revenue
actual Operation	- punctuality - headway adherence - average delays - capacity

Table 1: Influence Factors

3.2 Qualitative Impact Model

Once the influencing factors were identified, they were used to develop a qualitative model illustrating the most important causal relationships between factors. In the first stage of this analysis, the effective influence direction of a factor was defined as either “elevating”, if its increase leads to a numerical increase in the target indicator, or “diminishing” if it increase leads to a numerical decrease. The model only considered direct relationships since the indirect relationships are included in other direct relationships. For example, the frequency influences the number of vehicle-kilometers and is a direct relationship. In contrast, the influence of frequency on operation costs is indirect, and is already considered in the model by the direct relationship (vehicle-kilometers). Figure 2 illustrates the qualitative model developed using this process. Green lines are elevating influences and the red lines are diminishing influences.

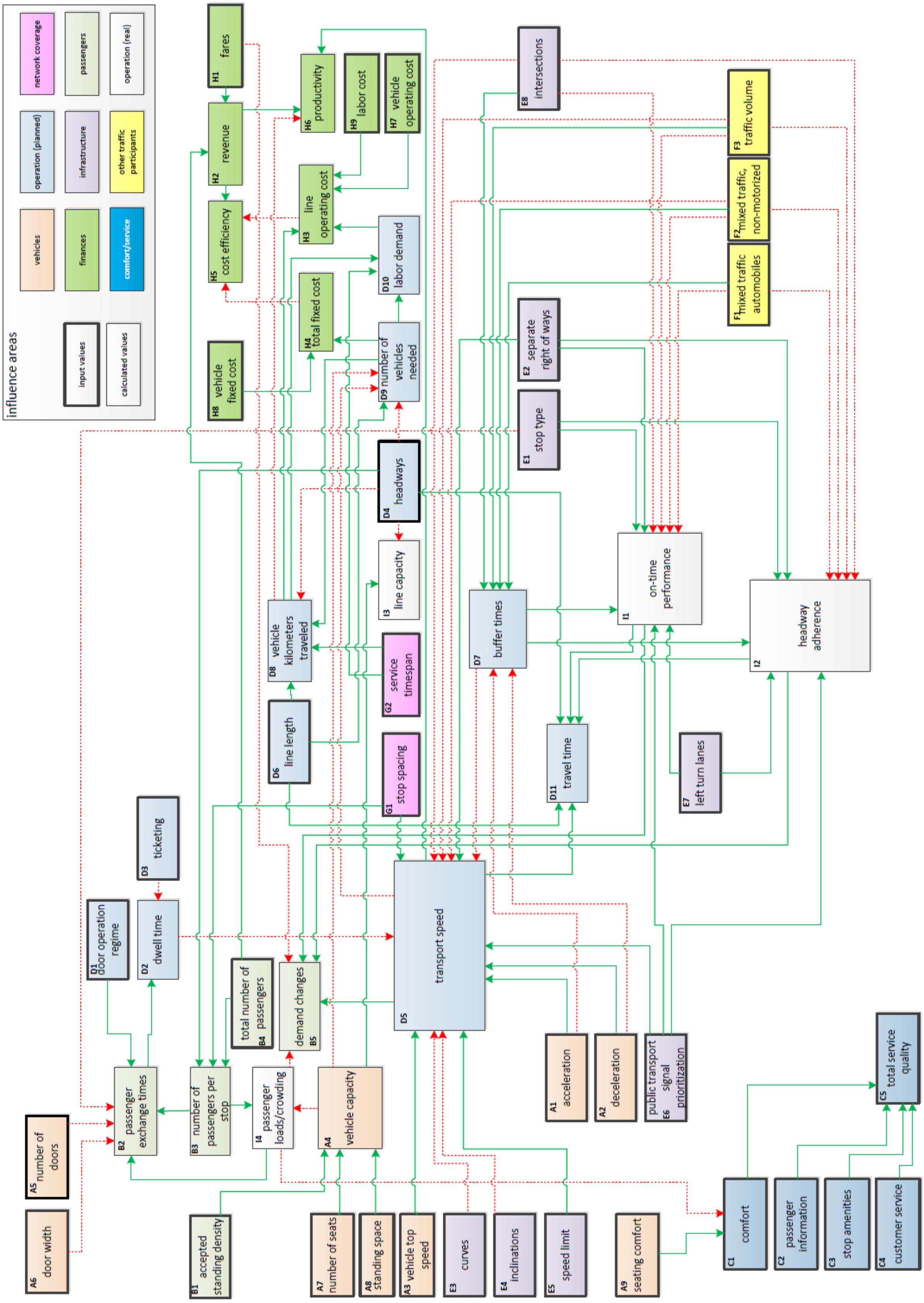

Figure 2: Qualitative impact model.

3.3 Quantitative Impact Model

The next step in the research was creating a quantitative model by adding mathematical equations describing the relationships identified in the qualitative model. Since the model was designed for use by non-professionals and did not need to be precise enough for detailed transport planning, it was built using a Microsoft Excel spreadsheet.

The model divides a public transit line in up to five sections, allowing for the modeling of changes in the infrastructure or other parameters along the line. The time frame basis is one hour, making it possible to study operations at different time periods (e.g. peak hours). The model requires users to enter basic input values, further interim/support values are largely generated or pre-set, however can be changed by the users for a more in-depth customization. Input values are values that are specified by users, such as vehicle characteristics, speed limits, stop distances or service headways. Interim/support values are needed in some stepwise calculations or as inputs that are unlikely to change. The model uses these inputs to calculate output values that describe the effect of changes to the public transport system. A feedback loop re-estimates the output values based on changes in passenger demand that take place as a result of the considered change. Model results are displayed as before and after values to provide a basic comparison of the situation before and after the given change. This summarizes the main factor changes and highlights the direction of change. Table 2 lists the input, interim/support and output values used in the model.

Inputs		
vehicle characteristics	**operation plan**	**infrastructure**
acceleration [m/s^2]	door operation regime (boarding /alighting at specific doors or all)	stop type (overtaking possible?)
deceleration [m/s^2]		fully separate right of ways [%]
top speed [km/h]	ticketing (e.g. proof-of-payment)	separate lanes [%]
number of doors [-]	headways [s]	num. curves with radius <50 m [-]
width of doors [m]	segment length [km]	speed limit [km/h]
standing space [m^2]	segment buffer times [%]	number of intersections [-]
vehicle length [m]	demand elasticity [-]	num. intersections with public transport signal priority [-]
seats per length [1/m]		
standing space per length [m^2/m]	**Quality and Availability**	num. intersections w. turn lanes [-]
	stop spacing [m]	num. intersections with left turn lanes and public transport signal priority [-]
passengers	average load factor [%]	
accepted standing density [P/m^2]	service timespan [h]	num. intersections at stops [-]
segment boarding passengers [-]	seating comfort (fulfillment of of criteria, measured as points achieved out of a possible total)	entry step height [m]
segment alighting passengers [-]		
		Traffic
Finance	passenger information (see above)	Share of line mixed with non-motorized transport [%]
income per passenger trip [CHF]	stop amenities (see above)	
operating cost [CHF/veh-km]	customer service (see above)	traffic flow stability (measured as coefficient of variation of public transport speed in mixed flow[1])
fixed cost per vehicle [CHF/d]		
labor cost [CHF/h]		
Interim and Support		
vehicle characteristics	**passengers**	**Finance**
capacity [-]	passenger exchange times [s]	hourly revenues [CHF]
door open/close times [s]	passengers per stop [-]	hourly cost of operation [CHF]
	door share of passenger amount [%]	fixed cost per hour [CHF]
Traffic	num. per door [-]	total scheduled services [min]
share of line in mixed operation [%]	door passenger exchange rate [-]	labor productivity [-]
	delay for uneven passenger distribution [-]	
Quality and Availability		**actual Operation**
crowding [-] (load factor based on cap. of seats + standing at 4P/m^2)	door system efficiency [-]	headway adherence [coeff. of variation]
	correction factor for standing passengers in door area [-]	
operation plan		capacity [P/h]
stop waiting times [s]	standing density [P/m^2]	average operation speed (without stops) [km/h]
dist. traveled per h [vehicle-km]	door capacity usage [-]	
Output		
transport speeds [km/h]	travel time [min]	productivity [CHF/veh-km]
vehicles needed [-]	total service quality rating	on-time performance [%]
drivers needed [-]	cost efficiency (rev./cost) [-]	average delay [s]
demand changes [%]		

[1] This was chosen so that the model could be applied with data collected by the public transport operator already so that no external data was needed. For future developments, the authors would like to consider measures made at the automobile flow itself.

Table 2 Inputs, Interim/Supports and Outputs

4. EXAMPLE: TRANSPORT SPEEDS

This section presents an example of how one relationship in the quantitative model is calculated (there are too many relationships in the model to describe them all in this paper). Speed is selected as the other relationships (e.g., vehicle capacity and load factor) are largely relatively simple. The selected relationship is for calculating public transport vehicle speed (including dwell times and stopping), one of the most critical values. Speed is both an output measure and is used to calculate several other values in the model as shown in Figure 3 .

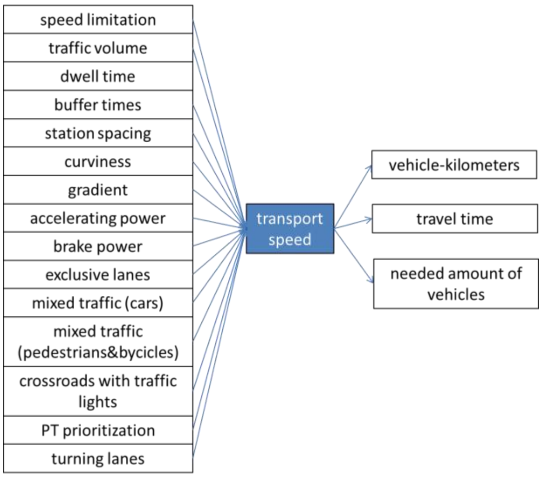

Figure 3 Influence and impact of transport speed (direct relationships).

4.1 Calculation of Public Transport Vehicle Speed

This section briefly summarizes how the model calculates public transport vehicle speed.

(1) Calculate maximum transport speed:

As shown in Equation 1, the maximum transport speed ($v_{t,max}$) is the minimum of the vehicle maximum speed (v_{max}), local speed limit (v_{lim}) and the top speed achievable considering vehicle acceleration (a_{acc}) / deceleration (a_{dec}) and stop spacing (d_{stop}).

$$v_{t,max} = \min\left(v_{max}, v_{lim}, \sqrt{\frac{2 \cdot d_{stop}}{\frac{1}{a_{acc}} - \frac{1}{a_{dec}}}}\right) \qquad \text{(Eq.1)}$$

(2) Calculate unrestricted travel time $t_{R,u}$

The unrestricted travel time is the sum of accelerating time t_{acc}, braking time t_{dec}, constant speed travel time t_{ct}, buffer time t_{Res} and the dwell-time t_H, with q_{Res} being the relative buffer time.

$$t_{R,u} = t_{acc} + t_{dec} + t_{ct} + t_{Res} + t_H \quad \text{with} \qquad \text{(Eq.2)}$$

$$t_{acc} = \frac{v_{t,max}}{a_{acc}}\ , \qquad \text{(Eq.3)}$$

$$t_{dec} = \frac{v_{t,max}}{-a_{dec}}\ , \qquad \text{(Eq.4)}$$

$$t_{ct} = \frac{d_{stop} - \frac{v_{t,max}^2}{2\cdot\left(\frac{1}{a_{acc}} - \frac{1}{a_{dec}}\right)}}{v_{t,max}} \text{ ,} \quad \text{(Eq.5)}$$

$$t_{Res} = q_{Res} \cdot (t_{acc} + t_{dec} + t_{ct}) \text{ .} \quad \text{(Eq.6)}$$

The dwell-time is calculated according to [19] and needs several vehicle parameters. The unrestricted travel time is calculated for three different cases: $t_{R,u,mix}$ for the whole section in mixed operation with motorized individual traffic ($v_{t,max}$ as shown before), $t_{R,u,nm}$ for the whole section in mixed operation with non-motorized traffic (defined $v_{t,max}$ = 10 km/h) and $t_{R,u,row}$ for the whole section with a separated right-of-way (defined v_{lim} = 60 km/h according to Swiss regulations for structurally separated tracks on streets).

(3) Calculate additional time for signalized intersections:

The model contains four intersection types:

- intersections without prioritization or left turn lanes
- intersection with public transport signal prioritization
- intersection with left turn lanes
- intersection with signal prioritization and left turn lanes

The additional time $t_{W,i}$ at intersection type *i* is multiplied by the number of intersections of type *i* ($n_{K,i}$), summed up for all intersection types and assigned relative to the reference stop spacing. Because this is done separately for intersections between stops and at stops, two specific waiting times were calculated. Equation 7 shows the calculation for the additional time in the case of intersections between stops ($t'_{W,Kn,btwstop}$), where l_A is the line segment length, $q_{K,btwstop}$ is the relative number of intersections (of the total number of intersections) between stops on the segment and $t_{Z,acc,dec}$ is time lost due to braking and accelerating at the intersection.

$$t'_{W,Kn,btwstop} = \frac{d_{stop}}{l_A} \cdot q_{K,btwstop} \cdot \sum_{i=1}^{4} n_{K,i} \cdot t_{W,i} + t_{Z,acc,dec} \quad \text{(Eq.7)}$$

Equation 8 shows the calculation of waiting time for intersections at stops ($t'_{W,Kn,atstop}$), in this case $t_{Z,acc,dec}$ is omitted since it assumed that the vehicle has already arrived at a stop. The share of intersections with stops on the line segment is $q_{K,atstop.}$:

$$t'_{W,Kn,atstop} = \frac{d_{stop}}{l_A} \cdot q_{K,atstop} \cdot \sum_{i=1}^{4} n_{K,i} \cdot t_{W,i} \quad \text{(Eq.8)}$$

(4) Calculate additional time due to traffic volume:

The model uses a simplified method with an addition of an extra time to the constant speed travel time via the variation-coefficient c_v as an indicator of automobile traffic volume and flow variation. This was chosen so that no additional data than what the public transport operator collects anyways is needed. It is assumed that if $c_v < 0.1$, public transport is unaffected by automobile transport. Otherwise, the travel time is extended by an additional time needed in mixed flow operations $t_{Z,mix}$.

$$t_{Z,mix} = \begin{cases} 0 & c_v < 0.1 \\ f(c_v) & c_v \geq 0.1 \end{cases}$$

(5) Calculate transport speed:

The results of these intermediate calculations can now be used to calculate transport speed v_t using Equation 9.

$$v_t = \frac{3.6 \cdot d_{stop}}{q_{mix} \cdot (t_{R,u,mix} + t_{Z,mix}) + q_{nm} \cdot t_{R,u,nm} + q_{sep,A} \cdot t_{R,u,row} + q_{sep,B} \cdot t_{R,u,mix} + t'_{W,Kn,btwstop} + t'_{W,Kn,atstop} + t'_{Z,Bg} + t'_{Z,inc}}$$

(Eq. 9)

Where:

q_{mix}	relative percentage of line in mixed operation with automobile traffic	[-]
q_{nm}	relative percentage in mixed operation with non-motorized transport	[-]
$q_{sep,A}$	relative percentage of fully separated right-of-ways	[-]
$q_{sep,B}$	relative percentage of separate lanes	[-]

with $$q_{mix} + q_{nm} + q_{sep,A} + q_{sep,B} = 1$$

$t'_{Z,Bg}$	additional time for narrow curves	[s]
$t'_{Z,inc}$	additional time for steep inclination	[s]

Transport speed is already an indicator for quality in public transport (and used e.g. in the TCQSM [4]) and has an influence on overall travel time. In addition to this, it influences the need for vehicles and thus affects costs and efficiency.

4.2 Validation with operational Data

The model was tested by comparing model output to measured values on two Verkehrsbetriebe Zurich (VBZ) lines: tram line 13 and trolley-bus line 46. These lines are shown in Figure 4. Both lines are radial routes serving large number of passengers throughout the day. The service headway is 7.5 minutes from early morning to late night, allowing for constantly high capacity. They were chosen because they travel over several different right-of-way conditions, making them especially helpful in testing how these relationships are implemented in the model. Tram line 13 has sections with a large number of pedestrians (*Zurich Bahnhofstrasse*) and sections with segregated tracks or mixed operation with cars. Bus line 46, has similar conditions, as well as a large section running through residential areas where separate right-of-ways are not available. The impact model was used to reproduce the lines with 5 sections. Table 3 presents the model outputs of punctuality (at -30/+60 seconds of scheduled time – the VBZ criterion), transport speed and travel time compared to measured values.

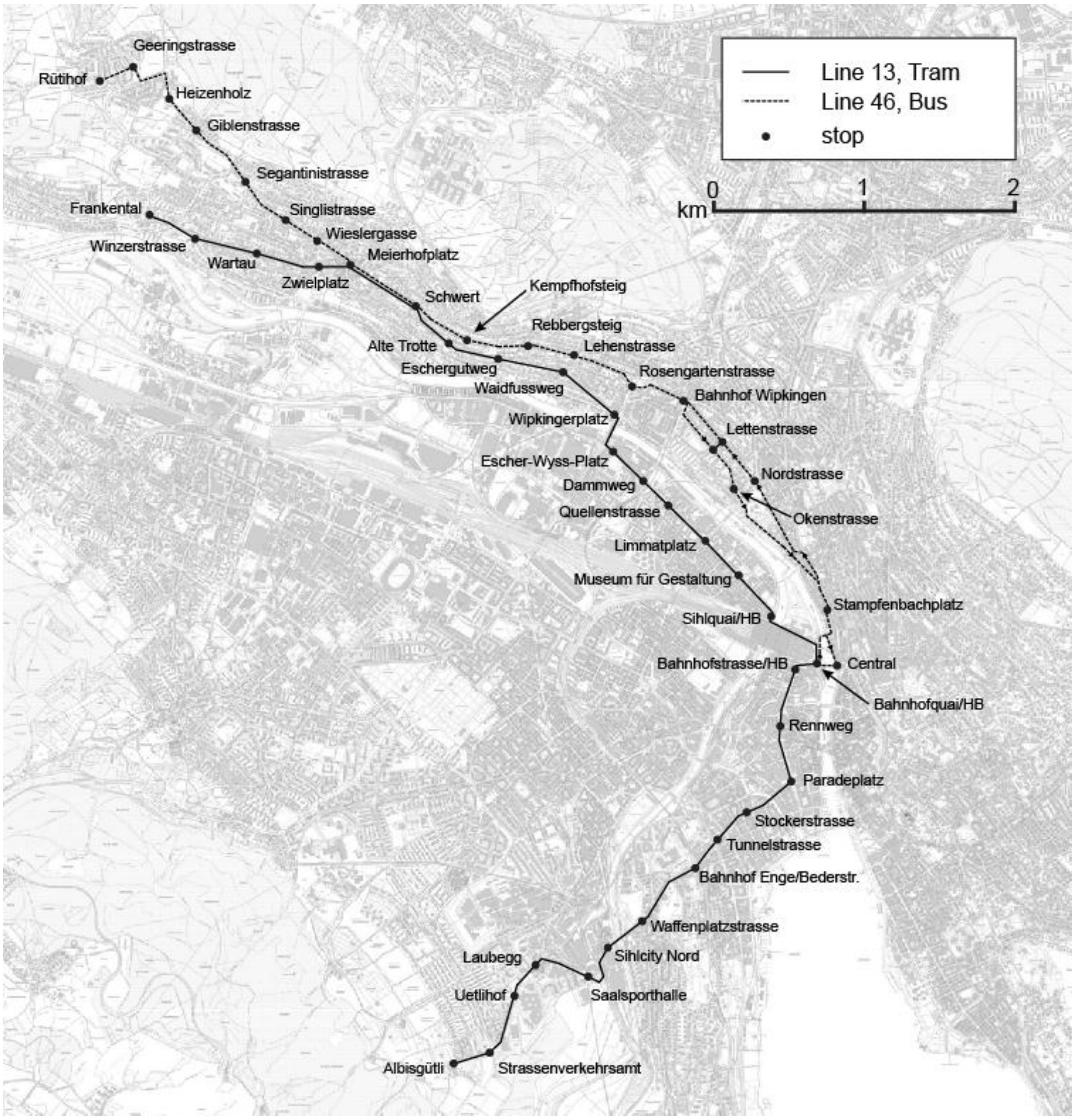

Figure 4 VBZ lines used for validation (map data from http://www.stadtplan.stadt-zuerich.ch, accessed July 6, 2012).

Line 13		**travel time**				**punctuality**			
		values [min]		**deviation**		**values [%]**		**deviation**	
direction	time period	model	measured	absolute [min]	relative	model	measured	absolute [%]	relative
Frankental - Albisgütli	07.00 - 08.00	43.8	45.1	-1.3	-2.88%	45%	36%	9.00%	25.00%
Frankental - Albisgütli	12.00 - 13.00	42.9	43.7	-0.8	-1.83%	72%	57%	15.00%	26.32%
Frankental - Albisgütli	17.00 - 18.00	44.8	45.2	-0.4	-0.88%	36%	29%	7.00%	24.14%
Albisgütli - Frankental	07.00 - 08.00	42.7	44.2	-1.5	-3.39%	85%	74%	11.00%	14.86%
Albisgütli - Frankental	12.00 - 13.00	43.4	43.8	-0.4	-0.91%	70%	61%	9.00%	14.75%
Albisgütli - Frankental	17.00 - 18.00	46.0	45.4	0.6	1.32%	53%	48%	5.00%	10.42%
Line 46		**travel time**				**punctuality**			
		values [min]		**deviation**		**values [%]**		**deviation**	
direction	time period	model	measured	absolute [min]	relative	model	relative	absolute [%]	relative
Bahnhofquai/HB -Rütihof	07.00 - 08.00	23.9	22.2	1.71	7.70%	73%	66%	7.00%	10.61%
Bahnhofquai/HB -Rütihof	12.00 - 13.00	23.8	22.3	1.48	6.64%	93%	80%	13.00%	16.25%
Bahnhofquai/HB -Rütihof	17.00 - 18.00	25.4	22.3	3.06	13.72%	75%	66%	9.00%	13.64%
Rütihof - Bahnhofquai/HB	07.00 - 08.00	26.8	25.6	1.17	4.57%	70%	70%	0.00%	0.00%
Rütihof - Bahnhofquai/HB	12.00 - 13.00	25.9	24.5	1.37	5.59%	83%	86%	-3.00%	-3.49%
Rütihof - Bahnhofquai/HB	17.00 - 18.00	26.4	25.1	1.27	5.06%	62%	67%	-5.00%	-7.46%

measured travel times:	planned time + mean delay			
travel time model:	calculated travel time including waiting times and delays			
punctuality:	measured over all stops on a line			
difference model – measured values:		over 15%		over 25%

Table 3 Comparison of Measured and Modeled Values

The results show that the model is quite accurate even though it includes many simplifications. One explanation for the relatively large differences in punctuality in three cases on line 13 is the presence of a stop in the middle of the line where driver changes occur, creating larger delays than passengers exchanges or other effects would. It would be possible to improve the results by adding more sections, however the gain would not justify the significantly increased complexity. Since the model goal is to develop a tool that can estimate the general impact of public transport network changes, this is not seen as necessary.

5. CASE STUDY MODEL APPLICATIONS

The research objective was to develop a simple model that could be used to examine the general impact of network changes on public transport operations. This section describes application of the model to a generic situation and to a specific route in Zurich.

5.1. Generic Application: Impact on Public Transport Speed

The generic case study examined the impacts on public transport vehicle speed of several typical operating conditions. The analysis begins by estimating the theoretically attainable speed. This is the ideal case reflecting an isolated transport system with no external disturbances. Speed is determined only by vehicle characteristics, safety requirements and regulations. The analysis was done for a short tram line with average passenger demand, operated with Zurich's “Cobra” type trams and a stop spacing of 350 m. Figure 5 shows the influence of five particular operating condition changes and the average transport speed along the line. The worst case, a tram line completely in a pedestrian area, illustrates the contrary to the theoretical case with segregated tracks and no buffer times. It has to be highlighted that this “shared spaces” approach is what is often propagated as a livable environment in which non-motorized transport and public transport would complement each other [18].

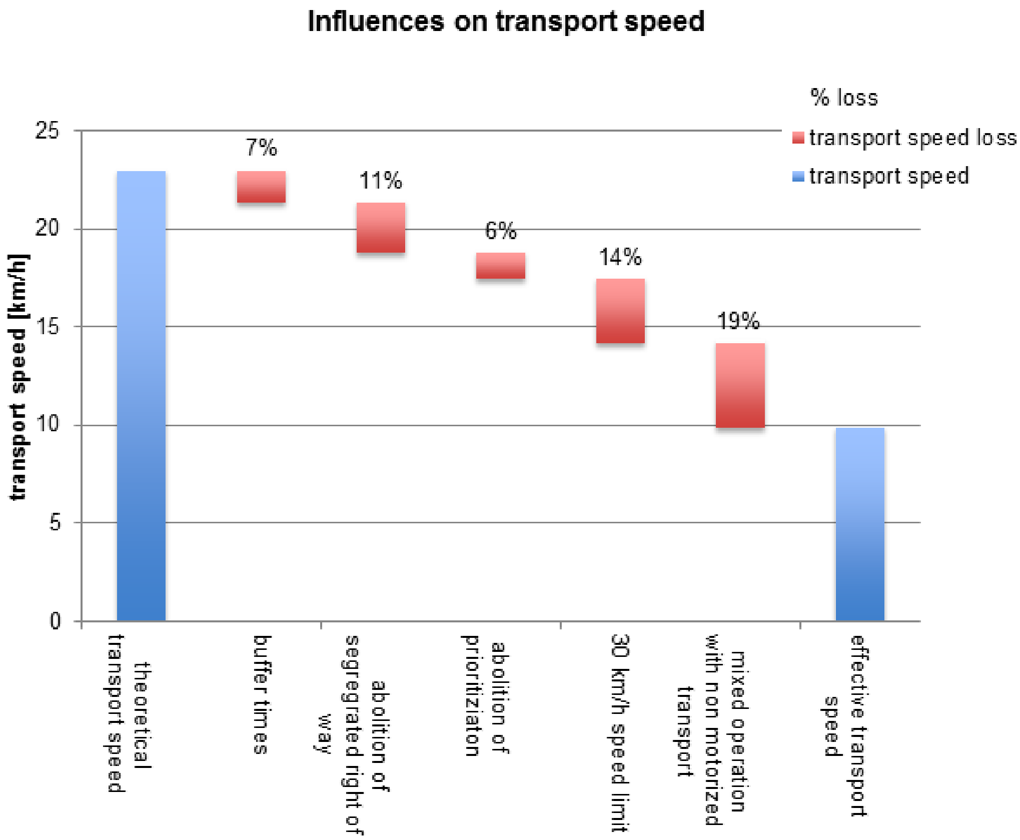

Figure 5 General impacts of selected measures on public transport speed

The generic case study shows the general impacts of several improvement measures and is used to derive a number of recommendations. These are useful for a rough analysis and e.g., for presenting preliminary ideas in non-technical committees. Specific recommendations were developed in the case of four key measures identified as the most potentially damaging consequences of the mobility strategy: The reduction of exclusive public transport right-of-ways, reduction of speed limits to 30 km/h, changes to stop spacing and introduction of "shared space" zones for public and non-motorized transport.

The analysis of a hypothetic example shows that if automobile traffic volumes are low, mixed traffic operations are unproblematic. However, when the automobile volume reaches levels where queuing occurs regularly, separate right-of-way should be provided on at least half of the line (better 60%) to prevent service irregularities. In most cases separate right-of-way is most effective at the beginning of a line. The benefits of separate right-of-way are very important to understand when considering, for example, inserting bicycle lanes on main streets, since this often requires eliminating exclusive public transport lanes. TABLE 4a presents recommendations for separate public transport right-of-way under different levels of automobile traffic.

Another popular planning measure today is creating 30 km/h zones with the intention of reducing noise and traffic volumes, while improving safety and increasing bike and pedestrian traffic. The impact of 30 km/h zones on public transport operations depends largely on passenger demand (impacting dwell times) and stop spacing. For stop spacing up to 250 meters it is possible to lower the speed limit to 30 km/h without a significant reduction in public transport quality.

For stop spacing between 250-350 meters introducing 30 km/h zones is likely to reduce public transport demand by up to 10%. However, at high passenger volumes, the influence of dwell-time on the overall travel time increases and the impact of stop-to-stop travel time decreases. Therefore, in these cases 30 km/h zones may be considered for stop spacing up to 450 meters. For larger stop spacing, 30 km/h zones lead to a significant loss in speed and are therefore not acceptable. (Note that the specific values have been developed using elasticities based on Swiss conditions, they will vary in other locations.)

A further popular measure is shared space or mixed traffic zones. In these areas all forms of transport operate at the same time. The generic analysis showed that mixed traffic zones with non-motorized traffic have a significant impact on public transport operations. For example a mixed traffic zone covering 8% of a 5-km route reduces passenger demand by approximately 5%, while a zone covering 12% (i.e. about 600-meters) reduces demand by about 10%. Given the fairly significant impact of these zones on public transport, it is important that these zones be very carefully designed so that capacity is not compromised for seemingly purely aesthetic reasons.

5.2. Case Study 1: Tram 13

The main goal (and the foreseen use of the model) was the application of the proposed public transport impact model to a specific situation in the city of Zurich. The case study was done on the tram line 13 which was also used in the model validation analysis described above. In the first step the line was divided into 5 segments in each direction. Segmentation was based on line characteristics, e.g., if there is mixed operation or a separate right-of-way. The input data was obtained based on the infrastructure, Zurich traffic information, as well as planning and operating data from the VBZ. The segmentation is shown in Figure 6. Segment 1 has separated right of way and high passenger volumes, segment 2 has only partial separated right of ways, segment 3 is one with separated right of ways again, however very high passenger volumes. In segment 4, the line traverses a pedestrian zone with accordingly very low speeds and large boarding/alighting volumes, finally, segment 5 is largely separate right of way with a high degree and prioritization medium to high passenger volumes due to a number of connecting stations and large activity centers along the route.

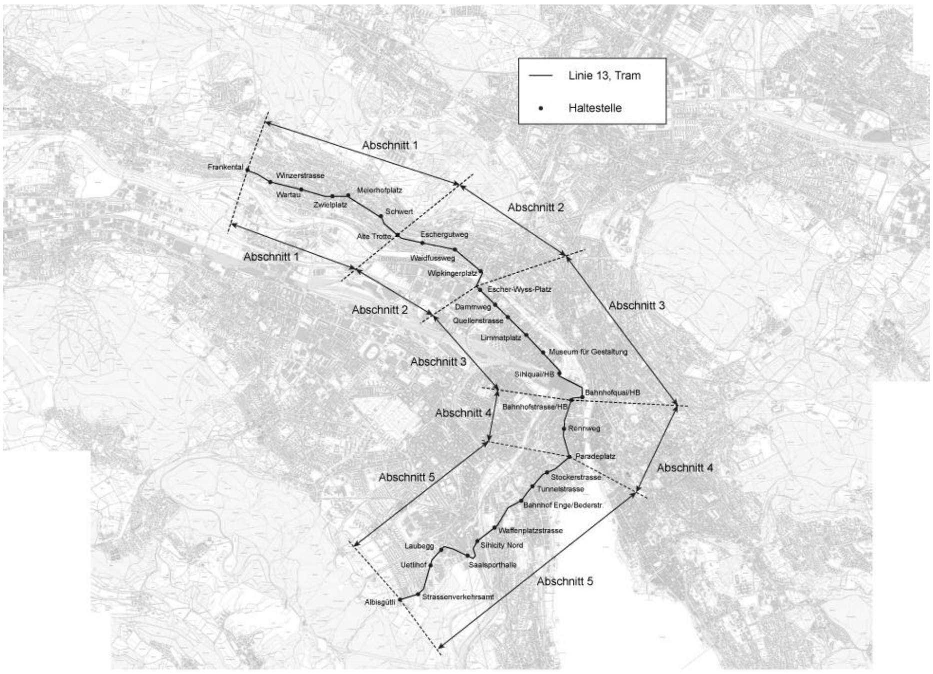

Figure 6: segmentation of tram line 13 (map based [17])

Three different scenarios derived from City of Zurich's mobility strategy were tested in the model:

1. A reduction in the separate right-of-way between *Sihlquai/HB* and *Frankental*. This would result from the creation of bike lanes since, in order to gain the needed space, the separation between trams and cars would need to be removed in many places.
2. A reduction of the separate right-of-way as in measure (1), however with an extension of stop spacing to at least 400 meters as a compensation
3. The creation of separate public transport right-of-way along the entire line, except on the '*Bahnhofstrasse'* (pedestrian street), and an extension of the stop spacing to 400 meters. This measure would significantly improve conditions for public transport by improving reliability and reducing travel times.

These three scenarios were tested using the impact model for the peak hour, when congestion and ridership are high. The selected time period is the evening peak with highest ridership and lowest reliability. The results of the model are summarized in Table 4.

Indicator		Scenario 1	Scenario 2	Scenario 3
Transport speed [km/h]	without	14.8	14.8	14.8
	with	14.14	14.67	16.67
	Δ abs.	-0.66	-0.13	1.87
	Δ %	-4%	-1%	13%
Travel time [min]	without	44.78	44.78	44.78
	with	48.98	47.22	38.21
	Δ abs.	4.2	2.44	-6.57
	Δ %	9%	5%	-15%
Punctuality [%]	without	36%	36%	36%
	with	15%	15%	74%
	Δ abs.	-0.21	-0.21	0.38
	Δ %	-58%	-58%	106%
Demand [%]		-8.0%	-9.3%	2.4%
Number of needed vehicles [-]	without	13	13	13
	with	13	13	12

Table 4 Results of the Line 13 Case Study

Scenario 1 leads to a remarkable worsening. Transport speed is reduced marginally, but the removal of the separate right-of-way causes a considerable reduction of punctuality, an increase in overall travel time and thus reduces demand (-8%). Due to parallel public transport routes in the area, the reduction may be lower, but a noticeable drop in demand is still to be expected.

In scenario 2, the reduction of transport speed is far less due to the longer stop spacing. Travel time increases by an acceptable 2.4 minutes. However, new mixed traffic zones lead to a worse punctuality. Furthermore, the larger stop spacings result in longer access times for the stops, leading to a reduction in demand that is even higher than in scenario 1. Therefore, the effect of the improvements with larger stop spacing (transport speed) is too small to compensate and, to the contrary, the lower reliability and longer access times exacerbate the situation.

Scenario 3 shows that adding separate right-of-way and increasing stop spacing can significantly improve operation, demand and efficiency. Travel time is reduced by 6.6 minutes due to increased speed. Punctuality is increased (+6%) and despite the longer access times created by longer stop spacing, the improvements in transport speed, punctuality and travel time lead to 2.4% increase in ridership. Furthermore, it is possible to operate with one vehicle less, allowing for a large cost reduction. These savings may even compensate for the cost of constructing the infrastructure.

5.3. Case study 2: Bus 46

Furthermore, bus line 46 was studied, for two main reasons: The degree of right-of-way separation is much lower and a large portion of the route is subject to considerations of implementing a 30km/h-zone. The segmentation is, again, using 5 segments as shown in Figure 7. Segment 1 is further divided into 2 sub-segments as during a large part, the two directions of travel use different alignments. In segment one, passenger volumes are very high while speeds are as they contain the terminal/initial stops of the line and coincide with major transfer nodes. Segment two is again subdivided due to different alignments for westbound and eastbound services, however the characteristics of the street are similar and they differ solely by segment length. The streets in this segment can be considered residential streets and are under consideration for 30 km/h zones. Segment 3 is similar, however the services are running on the same street, again, one with residential traits. In segment 4, the line can benefit from a stretch of separate right of way where it runs along a tram line. Furthermore, the streets are main streets and although traffic volumes can be high, this segment can be normally traversed with high speeds and few irregularities. Finally, segment 5 is a short end of line/beginning of line segment where the main road is left and a residential area is served. The turnaround takes places in a low traffic side street, so while speeds are low, there are almost no disruption from other traffic.

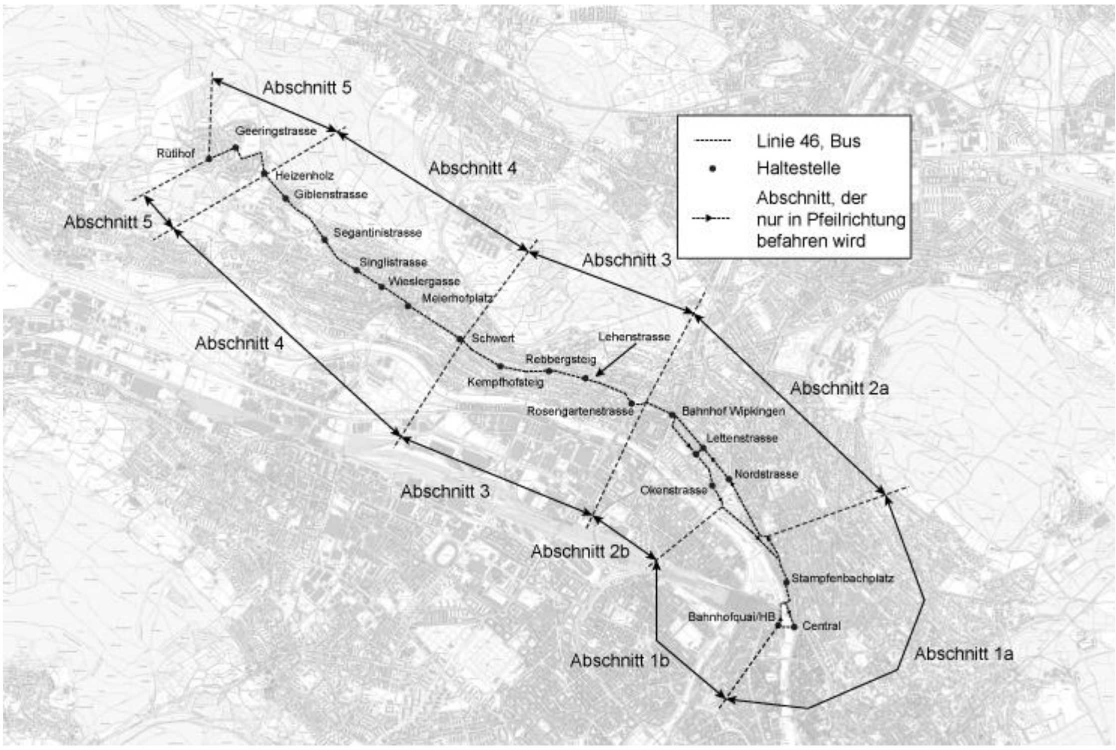

Figure 7: Segmentation for the line 46 case study (map based [17])

As with the previous case study, three scenarios were defined that would have more or less severe impacts on the line operation:

1. A 30km/h zone between the stops Stampfenbachplatz and Rosengartenstrasse. This measure would attempt to bring a noise reduction to areas that are primarily residential ones and is already part of the city of Zurich strategy [18].
2. A extended 30km/h variant in which the stretch from Rosengartenstrasse to Heizenholz is also included. Furthermore, in an attempt to implement dedicated bike lanes, the separate right of way segment would need to be run in mixed flow with road traffic. The goal of such a measure would be to maximize the noise reduction effects and also create an environment more suitable to non-motorized modes of transport.
3. As line haul speeds are already limited in many stretches of this line, a reduction stop spacing to no more than 350m in order to improve accessibility of the bus service is studied. This measure would be complemented by a new separate right of way be-

tween Rosengartenstrasse and Stampfenbachplatz so that the line speed would not be reduced.

Again, these three scenarios were tested for peak hour passenger and traffic volumes in order to assess the most critical case. The results are shown in

Indicator		Scenario 1	Scenario 2	Scenario 3
Transport speed [km/h]	without	18.49	18.49	18.49
	with	17.46	16.2	17.8
	Δ abs.	-1.03	-2.29	-0.69
	Δ %	-6%	-12%	-4%
Travel time [min]	without	26.41	26.41	26.41
	with	27.86	30.4	26.7
	Δ abs.	1.45	3.99	0.29
	Δ %	5%	15%	1%
Punctuality [%]	without	70%	70%	70%
	with	67%	49%	84%
	Δ abs.	-0.03	-0.21	0.14
	Δ %	-4%	-30%	20%
Demand [%]		-2.6%	-7.7%	3.9%
Number of needed vehicles [-]	without	8	8	8
	with	8	9	8

Table 5: Results of the line 46 case study

The result of the first scenario is that the total travel is increased by 5% and on time performance is reduced from 70% to 67%, resulting in a small (2.6%) reduction of passenger demand. As there are parallel lines nearby, the actual demand reduction is likely even lower and therefore the total impacts of this scenario are quite acceptable.

In the second scenario, the impacts are much larger, with a travel time increase of 15% and a new on time performance of 49%. This would lead to a reduction of demand of up to 7.7%. Another major drawback however is that an additional vehicle would be needed to operate services on this line, leading to large cost increases. Overall, the result of this scenario would be a major loss in quality while at the same time operating cost rises.

The third case would still lead to a travel time increase, however a very small one (1%), while reliability and accessibility can be significantly improved. This leads to a demand increase of almost 4% (not considering shift from other lines).

5.4. Case study conclusions

The case studies show that every change to the public transport systems needs to be considered very carefully. While a number of measures derived from the mobility strategy can be applied with little negative impact, wide spread and large scale measures can severely impact public transport performance and increase cost, leading to a higher need for subsidies or higher fares. Also, the case studies gave a short introduction into how the model can be applied.

6. CONCLUSIONS

This paper describes the development and application of a high-level model designed to evaluate the impact of common measures on public transport operations. The model was developed especially to show the impact of various right-of-way changes to non-professionals. It allows users to analyze generic relationships in public transport systems and to estimate the impact of measures on the traffic network. For the Zurich network, it was possible to show the conflict between measures aimed at making the city more bicycle and pedestrian friendly versus measures designed to improve public transport efficiency. The model helps users understand how small changes along a line could negatively impact public transport performance. The results show that reducing separate right-of-ways can cause a major loss of quality. On the other hand they also show that introduction of 30 km/h zones can be acceptable in areas with short stop spacing or high passenger demand. These analyses highlight how important separated right-of-way is for urban public transport. Adding separate right-of-way can significantly improve public transport quality and productivity. At the same time, this shows the vulnerability of public transport to the removal of dedicated lanes. In the case of Zurich, the insertion of bicycle lanes and thus the reduction of separate right-of-way has to be balanced carefully. Otherwise, an undesirable and serious loss of quality due to less reliable transport and longer travel times may happen. It must be emphasized that the authors are not opposed to the introduction of 30 km/h zones or shared-space concepts in general, however these measures must be very carefully designed to avoid reducing public transport quality and efficiency. Furthermore, the trade-off between measures must be clearly understood by decision-makers and the public.

The impact model is not a planning tool and delivers estimated values which are accurate enough to estimate the impact of changes on the network, as the comparison with measured values showed. However, especially the changes in passenger demand are to be considered carefully. The estimation of the impact on passenger demand is based on elasticities measured in Switzerland. The model considers the modelled tram or bus line in an isolated environment, however in real operations there may be parallel lines with interrelationships. It is possible to assess if a measure influences the further connections at the end of the line, but it is not possible to simulate a line in the context of a network. Loss in passenger demand can thus be lower due to alternative routes. Overall, the model delivers the tendency and scale caused by changes on the network. The expansion of the model, with the inclusion of further factors and influences (network level) could be the topic of further research.

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