Multi user-class urban public transport network design

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Urban public transport network design can be looked upon as a bi-level problem. The upper level relates to the public transport planner who decides how the public transport network should look given a specific design objective, while the lower level represents the way travellers will use the network that is proposed. In this approach the public transport planner has to consider the impact of his design decisions on traveller behaviour with respect to the decision to use the network or not, and the traveller’s valuation of the time elements of a public transport trip (access time, waiting time, in-vehicle time, transfers, and egress time).

Literature on public transport network design usually focuses on the controversy between the traveller’s and the operator’s interests. The description of traveller behaviour is often limited to a single traveller group, that is the average traveller. This is especially true for analytical network optimisation models, see e.g. Kocur & Hendrickson (1982), Chang & Schonfeld (1991), Spasovic et al. (1994), Van Nes & Bovy (2000). Literature on travel behaviour, however, shows that there are large differences in traveller groups with respect to the valuation of the travel time elements as well as with the sensitivity for the quality of the services offered (Van der Waard (1988), Wardman (2001)). Elderly, for instance, have high weights for access and egress time, while travellers lacking adequate alternatives are likely to use public transport even though the quality offered might be far from optimal. Furthermore, the notion of the average traveller also deserves extra attention. The average traveller might be related to public transport users, to potential public transport users, or to all travellers. In each case the perception of the public transport service quality will differ.

Given such differences between traveller groups, it is certainly relevant to distinguish different traveller groups in public transport network design. Such a distinction leads to a more realistic description of the relationship between supply and demand. Furthermore, it might lead to a better public transport network design, and finally it allows a more detailed analysis of the costs and benefits of the public transport system.

Ideally all travellers should be accounted for in public transport network design. Since some traveller groups do not consider public transport as a realistic alternative, the definition of all travellers will be limited to potential public transport users, which consist of travellers having alternatives but who might use public transport, and travellers who lack adequate transport alternatives. The latter distinction is also relevant from a political point of view: should public transport focus on travellers who have to use public transport (captive) or should public transport be a true alternative for private car (choice-travellers)?

This paper focuses especially on the impact of distinguishing different traveller groups on urban public transport network design. A new analytical optimisation model for urban public transport network design will be presented in which two different traveller groups are considered simultaneously. The results of this multi user-class network optimisation will be compared with the traditional single user-class approach.
The paper is structured as follows. First a brief description is given of the single user-class public transport network design problem. Next, relevant differences between traveller groups will be discussed, including a numerical example of the possible impact of focussing public transport network design on specific traveller groups. Then, the multi user class public transport network design model is presented, which is followed by an application for an urban bus-corridor. Finally, the conclusions that can be drawn from this analysis are discussed.
2.1 General structure

The single user-class public transport network design model is based on the analytical model of Van Nes & Bovy (2000) and Van Nes (2000, 2002). The analytical model for public transport network design is formulated for an urban corridor in which parallel bus lines offer public transport services to the city centre (see Figure 1). The decision variables are the stop spacing ($S_s$), line spacing ($S_l$), and the frequency ($F$). Fares are assumed to have a fixed value, since they are no network characteristic.

The design objective that is used is maximising social welfare, which is according to Berechman (1993) the most suitable objective for urban public transport network design. This objective accounts for the benefits for the traveller as well as those for the operator, using the economic concepts of consumer surplus and producer surplus. In this analysis it is assumed that there are no additional benefits for providing urban public transport. This assumption is in line with guidelines for economic assessment of transport infrastructure projects (Ministry of Transports, Public Works and Watermanagement (1996)).

The decision variables stop spacing, line spacing and frequency determine the quality of the services offered in terms of door-to-door travel times. Similarly, the decision variables determine operational costs. The travel times influence the actual patronage, which determines the revenues. Revenues and operational costs determine producer surplus of profit, which together with consumer surplus, determined by patronage and travel times, yields social welfare. Given these relationships between decision variables and the objective function of social welfare it is possible to determine optimal values for the decision variables.

![Figure 1: Layout of the public transport network in the urban corridor](image)

2.2 Mathematical formulation

The mathematical formulation of the public transport network design problem is based on a unit area of one square kilometre. The travel time to the city centre ($T_c$) consists of access time, waiting time, in-vehicle time, and egress time.
\[ T_c = w_a \cdot \frac{f_a \cdot (S_s + S_l)}{V_a} + w_w \cdot \frac{f_w \cdot L_c}{S_s} \cdot \left( \frac{S_s}{V} + T_s \right) + w_e \cdot T_e \]  

with:

- \( S_s \) = stop spacing
- \( S_l \) = line spacing
- \( F \) = frequency
- \( f_a \) = access factor
- \( V_a \) = access speed
- \( f_w \) = factor for the waiting time
- \( L_c \) = average travel distance to city centre
- \( V \) = maximum speed
- \( T_s \) = time lost at a stop
- \( T_e \) = egress time
- \( w_k \) = weight for time element \( k \)

The patronage or public transport usage \( (P(T_c)) \) is given by a logit mode-choice model:

\[ P(T_c) = P_0 \cdot \frac{\exp(-\alpha \cdot T_c - \beta)}{\exp(-\alpha \cdot T_c - \beta) + \sum_{m=1}^{n_m} \exp(-\alpha_m \cdot T_m)} \]  

where:

- \( P_0 \) = total travel demand for transport per square kilometer in trips
- \( \alpha \) = demand sensitivity to public transport quality
- \( \beta \) = mode specific constant for public transport
- \( n_m \) = number of modes excluding public transport
- \( \alpha_m \) = demand sensitivity for mode \( m \)
- \( T_m \) = weighted travel time for mode \( m \)

The consumer surplus \( (CS) \) is defined as the integral of the travel demand from \( T_c \) to infinity, which is approximated by a triangle:

\[ CS = 0.5 \cdot P(T_c) \cdot (T_z - T_c) \cdot c_t \]  

where:

- \( T_z \) = travel time where the demand for public transport vanishes in case of a linear approximation of the logit - function
- \( c_t \) = value of time for passengers

The producer surplus \( (PS) \) consists of the revenues minus the operational costs:

\[ PS = R - C - r \cdot P(T_c) \cdot c_t \cdot \frac{1000}{1000} \cdot \frac{1000}{1000} \left( \frac{S_s}{V} \times T \right) \]
\[ C_o = \text{operational costs} \]
\[ r_t = \text{fare paid by the traveller} \]
\[ c_o = \text{operational costs, that is, driver and vehicle costs per vehicle hour} \]

The objective function for social welfare \((SW)\) is then defined as:

\[
SW = 0.5 \cdot P(T_c) \cdot (T_z - T_c) \cdot c_t + r_t \cdot P(T_c) - \frac{c_o \cdot F \cdot 1000}{S_l} \cdot \frac{1000}{S_s} \left( \frac{S_s}{V} + T_s \right) \cdot 2
\]

(5)

2.3 Application

2.3.1 Main characteristics

The analytical model described in the previous section is applied to the case of an urban bus corridor such as found in the Dutch city of Utrecht having the following characteristics:
- Stop spacing 350 metres;
- Line spacing 550 metres;
- Frequency 5 vehicles per hour;
- Average travel distance 3 kilometres;
- Patronage of 100 travellers per square kilometre per hour.

This corridor will be used as a benchmark for the results of the network optimisation in Section 2.3.4.

Please note that the total demand for public transport is unknown. However, given a description of travel behaviour it is possible to estimate the related level of demand. The description of travel behaviour is divided into two parts:
- Weights for the time elements
- Sensitivity for the quality of the services offered.

The first part focuses on the traveller’s perception of the different trip time elements, while the second part deals with the actual mode choice, that is the relationship between supply and demand. In the latter case a mode specific constant will be used to account for the differences in transport alternatives and in attitude to public transport in general.

2.3.2 Travel time weights

Van der Waard (1988) presents weights for the travel time elements for the average public transport passengers as well as specific passenger groups based on gender, car availability, age, trip purpose, and so on. In this analysis a distinction is made between travellers who have a car available for the trip (CA) and those who have not (NCA). These two traveller groups show clearly different weights for all travel time elements,
while for a distinction with respect to trip purpose or age, some traveller groups were too small to determine significant values for the weights. Although these weights are based on public transport users only, they are assumed to be representative for all potential public transport users. It should be noted that the range of these weights are in line with those generally found in literature (see e.g. Wardman (2001)).

Van der Waard (1988) estimated the weights for both passenger groups simultaneously, thus allowing for a comparison between the weights for both passenger groups. Travellers having a car available, for instance, have a 56% higher weight for in-vehicle time than travellers without a car available. Therefore, the weights for travellers having a car available can be scaled in two ways:

- For each group separately using the weight of the in-vehicle time for each traveller group;
- Using the smallest weight of the in-vehicle time of all groups, that is the weight for the traveller group without a car available. These weights are referred to as high weights.

<table>
<thead>
<tr>
<th>Table 1: Weights for the trip time elements and parameters for different groups of public transport users (Van der Waard (1988))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Element</strong></td>
</tr>
<tr>
<td>----------------------------------------</td>
</tr>
<tr>
<td><strong>Access time (W_a)</strong></td>
</tr>
<tr>
<td><strong>Waiting time first stop (W_w)</strong></td>
</tr>
<tr>
<td><strong>In-vehicle time (W_i)</strong></td>
</tr>
<tr>
<td><strong>Egress time (W_e)</strong></td>
</tr>
<tr>
<td><strong>(\alpha)</strong></td>
</tr>
<tr>
<td><strong>(\beta)</strong></td>
</tr>
</tbody>
</table>

The weights used in the analysis are summarised in Table 1. Please note that the weights for travellers without a car available for the trip are nearly equal to those of the average traveller. This is due to the fact that this traveller group accounts for about 80% of the public transport users. In the remainder of this paper is assumed that these weights determined for public transport users are representative for the potential public transport users. Other differences between traveller groups will be incorporated in the demand model.

2.3.3 Demand model

The relationship between demand and supply is described using the logit mode choice model given in Equation 2. Since there is no calibrated demand model available for this analysis, pragmatic estimates are used for the parameters of the demand model and the related level of demand. The demand sensitivity \(\alpha\) is assumed to be 0.03 \(\text{min}^{-1}\) for all traveller groups. It is assumed that the difference in mode choice is primarily determined by the mode-specific constant, which accounts for a bias to other modes.
126 travellers per square kilometre per hour. If it is assumed that the demand of travellers having a car available and willing to opt for public transport is twice as large, the total demand for public transport to the city centre amounts to about 377 travellers per square kilometre. Travellers who do not consider public transport as an alternative are excluded from the analysis.

Finally, the mode-specific constants are determined for the average traveller and the CA-traveller group such that given the total demand of 377 travellers and 252 travellers per square kilometre per hour, the resulting patronage equals 100 and 20 passenger per square kilometre per hour respectively (see Table 1). The high values for the mode-specific constant clearly show the bias to using private modes, especially for the CA-traveller group. The impact of these mode specific constants is illustrated by the resulting public transport shares for urban trips to the city centre: 63.6% for NCA-travellers, 8.0% for CA-travellers and 26.5% for all travellers.

2.3.4 Analysis

Given these estimated weights and parameters for the description of the relationship between supply and demand, the optimal network characteristics are determined for four scenarios:

1. Average traveller;
2. Travellers having no car available;
3. Travellers having a car available while assuming normal weights;
4. Travellers having a car available while assuming high weights.

In each scenario the patronage in the reference case is assumed to be equal to 100 passengers per square kilometre. This implies that in case of specific traveller groups the level of demand ($P_0$) is artificially increased in order to achieve a comparable level of patronage for the reference situation. Since the NCA-travellers account for 80% of the patronage the level of demand is increased by 25%, while for CA-travellers the level of demand is five times higher. Of course, these assumptions are not realistic but they prevent that the large difference in patronage will determine the differences between the scenarios. Please note that the case of high weights for the CA-traveller group is identical to using normal weights and a 56 % higher demand sensitivity $\alpha$ (that is $\alpha = 0.047 \text{ min}^{-1}$).

**Table 2: Optimal network characteristics for four scenarios (single user-class network design)**

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>Average</th>
<th>NCA</th>
<th>CA normal weights</th>
<th>CA high weights</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stop spacing [m]</strong></td>
<td>350</td>
<td>623</td>
<td>607</td>
<td>746</td>
<td>703</td>
</tr>
<tr>
<td><strong>Line spacing [m]</strong></td>
<td>550</td>
<td>681</td>
<td>649</td>
<td>1005</td>
<td>805</td>
</tr>
<tr>
<td><strong>Space accessibility [/km$^2$]</strong></td>
<td>5.2</td>
<td>2.4</td>
<td>2.5</td>
<td>1.3</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>7.0</td>
<td>6.0</td>
<td>8.0</td>
<td>10.0</td>
</tr>
<tr>
<td>--------------------------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td><strong>Time accessibility [h]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Speed [km/h]</strong></td>
<td>20.7</td>
<td>27.7</td>
<td>27.4</td>
<td>29.8</td>
<td>29.1</td>
</tr>
<tr>
<td><strong>Travel time [min]</strong></td>
<td>20.8</td>
<td>18.5</td>
<td>19.1</td>
<td>19.2</td>
<td>17.7</td>
</tr>
<tr>
<td><em>(unweighted)</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Operational costs [€/km²]</strong></td>
<td>68.2</td>
<td>57.8</td>
<td>52.5</td>
<td>41.6</td>
<td>66.3</td>
</tr>
<tr>
<td><strong>Travel time NCA [min]</strong></td>
<td>26.7</td>
<td>25.5</td>
<td>26.5</td>
<td>28.8</td>
<td>25.9</td>
</tr>
<tr>
<td><strong>Travel time CA [min]</strong></td>
<td>29.8</td>
<td>27.1</td>
<td>28.2</td>
<td>28.6</td>
<td>40.8</td>
</tr>
<tr>
<td><strong>Patronage</strong></td>
<td>100</td>
<td>102</td>
<td>100</td>
<td>103</td>
<td>119</td>
</tr>
<tr>
<td><strong>Consumer surplus</strong></td>
<td>235</td>
<td>235</td>
<td>450</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td><strong>reference network [€/km²]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Consumer surplus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>optimised network [€/km²]</strong></td>
<td>-</td>
<td>245</td>
<td>451</td>
<td>47</td>
<td>80</td>
</tr>
<tr>
<td><strong>Social welfare</strong></td>
<td>201</td>
<td>201</td>
<td>416</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td><strong>reference network [€/km²]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Social welfare</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>optimised network [€/km²]</strong></td>
<td>-</td>
<td>222</td>
<td>433</td>
<td>41</td>
<td>54</td>
</tr>
</tbody>
</table>

* high weights

The network characteristics for the reference network and for these four scenarios are shown in Table 2. They include the decision variables stop spacing, line spacing and frequency (that is time accessibility), and the resulting performance characteristics such as speed, travel time (unweighted and for each traveller group), operational costs, patronage, consumer surplus, and social welfare. Please note that due to the different descriptions of travel behaviour, the values for the consumer surplus and thus social welfare differ substantially between the scenarios. A comparison with the values for the reference situation is more suitable. Therefore, the values for the reference network are included for each scenario.

For the optimal networks the resulting stop spacing and line spacing are always larger than in the reference situation. Space accessibility should thus be lower, while time accessibility (that is frequency) should be higher than in the reference situation. Larger stop spacing leads to higher speeds. The unweighted travel times are all substantially lower than in the reference situation, just as operational costs.

With respect to the weighted travel times, however, the lowest travel times are found in the case that the average traveller is considered. At first sight, this finding seems counter-intuitive. It would seem more logical that a network that is designed for a specific traveller group would yield the lowest travel time for that traveller group. This line of reasoning, however, ignores the fact that in network design a balance is found between travellers' interests and those of the operator. Due to the different preferences of each traveller group, the value and especially the sensitivity of the consumer surplus will be different in each scenario. Please note that the differences for the consumer surplus are very large. In the case of specific traveller groups this has resulted in optimal networks having lower operational costs. This is
the lowest operational costs. In the case of high weights, however, the sensitivity for changes in the network is larger and the balance shifts in favour of this category of travellers once again, yielding the most expensive network from all optimal networks.

The consequences of designing for specific traveller groups only instead of designing for the average traveller are illustrated in Figure 2. Compared to the average traveller, travellers without a car available prefer denser networks having lower frequencies, yielding lower operational costs. Travellers who can use a car for their trip would accept coarser networks having higher frequencies. Operational costs would be lower. In the case of high weights, however, space accessibility is still somewhat lower, but time accessibility should be substantially increased, which leads to slightly higher operational costs. Please note that the unweighted travel times and speed are almost equal for all scenarios.

![Figure 2: Relative changes in network characteristics for specific traveller groups (100% is the average traveller)](image)

**2.3.5 Conclusions**

This analysis clearly shows that it really matters which traveller group a public transport network is designed for. It influences the network characteristics, especially the trade-off between space accessibility and time accessibility, as well as the operational costs of the resulting network. The choice for which traveller group the public transport network is designed for is clearly a political one. Interestingly, this analysis also shows that from the traveller's perspective, the network designed for the average traveller is most attractive. Although this finding might be the result of the numerical values used in this example, it illustrates that focusing on specific populations might not always lead to better network designs. Furthermore, the analysis showed that modifying the network to attract travellers having realistic
alternatives adds very small amounts to consumer surplus and social welfare. This finding implies that from a social welfare point of view attracting car-users is not a suitable objective.
3.1 Introduction

The previous section illustrated the impact of focussing on specific traveller groups in public transport network design. In practice, however, public transport users come from different traveller groups having different preferences towards public transport attributes. It is thus preferable to account for their characteristics simultaneously, instead of focussing only on specific traveller groups. This more realistic description of traveller behaviour might lead to better network designs, and allows for a more detailed analysis of the costs and benefits of specific network designs, especially with respect to different traveller groups.

This approach requires an extension of the public transport network design model discussed in the previous section, which will be presented in this section. This newly developed extended model will be applied to the same corridor. The results will be compared to those for the traditional single user-class network design.

3.2 Extension of the single user-class network design model

3.2.1 Demand side

If different traveller groups are distinguished, the formulation of the travel time and the relationship between supply and demand will depend on the traveller group. Thus the patronage and the corresponding consumer surplus will vary between the traveller groups. Summation of the consumer surplus per traveller group yields the total consumer surplus. These extensions of the single user-class network design problem are illustrated in Figure 3.

3.2.2 Supply side

On the supply side, the extension is relatively simple. The revenues are the summation of the revenues from each traveller group. The operational costs of the network, however, are not influenced by distinguishing different traveller groups.
3.2.3 Mathematical formulation

The equation for the travel time for traveller group $x$ becomes:

$$T_{c,x} = w_{a,x} \cdot \frac{f_a \cdot (S_a + S_l)}{V_a} + w_{w,x} \cdot \frac{f_w}{F} + w_{l,x} \cdot \frac{L_c}{S_s} \cdot \left( \frac{S_s}{V} + T_s \right) + w_{e,x} \cdot T_e$$  \hspace{1cm} (6)

Please note that in this formulation all other characteristics such as access speed of trip length are assumed to be independent of the traveller group that is considered.

The patronage for traveller group $x$ is described by:

$$P_x(T_{c,x}) = P_{0,x} \cdot \frac{\exp(-\alpha_x \cdot T_{c,x} - \beta_x)}{\exp(-\alpha_x \cdot T_{c,x} - \beta_x) + \sum_{m=1}^{n_m} \exp(-\alpha_{m,x} \cdot T_{m,x})}$$  \hspace{1cm} (7)

The social welfare objective function ($SW$) is then defined as the sum of the consumer surplus for all traveller groups plus the sum of the revenues from all traveller groups minus the operational costs:
\[ c_o \cdot F \cdot \frac{1000}{S_i} \cdot \frac{1000}{S_s} \cdot \left( \frac{S_s}{V} + T_s \right) \cdot 2 \]

Please note that in this specification the traveller’s value of time and the fares are assumed to be identical for all traveller groups. A limited sensitivity analysis showed that this assumption does not influence the interpretation of the results. In the case that the traveller groups are all equal with respect to travel preferences, that is in terms of time weights, sensitivity for service quality and mode specific constant, the sum of \( P_{0,r} \) will equal \( P_0 \), and thus equation 8 will then equal equation 5.

3.3 Application of the model

The new multi user class network design model is applied to the same urban corridor as the single user-class network design model while using similar assumptions. A distinction is made between travellers having a car available and travellers who have not. In the reference situation the total patronage is 100 passengers per square kilometre, of which 80% does not have a car available for the trip. The total level of demand is about 377 travellers per square kilometre. The traveller group having a car available and willing to choose public transport is twice the size of the traveller group without a car available.

The following three scenarios are analysed:
1. Normal weights for both traveller groups and equal sensitivity for the service quality (\( \alpha_{NCA} = \alpha_{CA} = 0.03 \)) (see columns 3 and 4 in Table 1);
2. High weights for travellers having a car available and equal sensitivity for the service quality for both traveller groups (\( \alpha_{NCA} = \alpha_{CA} = 0.03 \)) (see columns 3 and 5 in Table 1);
3. Normal weights for both traveller groups while travellers with a car available are more sensitive for service quality offered than travellers without a car available (\( \alpha_{NCA} = 0.02 \) and \( \alpha_{CA} = 0.04 \)).

Please note that the second scenario, that is high weights for travellers having a car available while assuming a and constant sensitivity for transport service quality is equivalent to adopting normal weights while assuming a larger sensitivity for transport service quality. The third scenario, in which a difference in demand sensitivity is explicitly accounted for, the total demand is slightly lower than 377 travellers per square kilometre per hour in order to have a patronage of 100 passengers per square kilometre per hour for the reference network.

In all cases a comparison is made with the results of the single user-class model based on the average traveller. The results of this analysis are shown in Table 3. For comparison this table also includes data for the reference situation. In addition to the results in Table 2 the outcome for the public transport share is included as well. With respect to the values for social welfare it must be noted that since each scenario has its own specification of travel preferences, the values for social welfare are only comparable within a scenario and not between scenario’s.
The first finding to be noted is that the optimal values for stop spacing, line spacing, and frequency are almost equal for all scenarios. Apparently, the more detailed specification of travel demand has limited influence on the optimal network characteristics. Consequently, the differences in speed and travel times are very small. In scenarios 1, 2 and 3, the larger line spacing leads to slightly lower operational costs compared to the single user-class scenario.

Table 3: Optimal network characteristics for the single-user class network design model and for three scenarios using the multi user-class network design model

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>Single user-class</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop spacing [m]</td>
<td>350</td>
<td>623</td>
<td>634</td>
<td>631</td>
<td>639</td>
</tr>
<tr>
<td>Line spacing [m]</td>
<td>550</td>
<td>681</td>
<td>729</td>
<td>701</td>
<td>745</td>
</tr>
<tr>
<td>Space accessibility [/km²]</td>
<td>5.2</td>
<td>2.4</td>
<td>2.2</td>
<td>2.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Time accessibility [/h]</td>
<td>5.0</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Speed [km/h]</td>
<td>20.7</td>
<td>27.7</td>
<td>27.9</td>
<td>27.8</td>
<td>28.0</td>
</tr>
<tr>
<td>Travel time [min] (unweighted)</td>
<td>20.8</td>
<td>18.5</td>
<td>18.7</td>
<td>18.6</td>
<td>18.7</td>
</tr>
<tr>
<td>Operational costs [€/km²]</td>
<td>68.2</td>
<td>57.8</td>
<td>53.5</td>
<td>55.8</td>
<td>52.2</td>
</tr>
<tr>
<td>Weighted travel time NCA [min]</td>
<td>26.7</td>
<td>25.5</td>
<td>26.5</td>
<td>26.2</td>
<td>26.6</td>
</tr>
<tr>
<td>Weighted travel time CA [min]</td>
<td>29.8</td>
<td>27.1</td>
<td>27.5</td>
<td>43.2*</td>
<td>27.6</td>
</tr>
<tr>
<td>Patronage [/km²]</td>
<td>100</td>
<td>102</td>
<td>102</td>
<td>103</td>
<td>102</td>
</tr>
<tr>
<td>Public transport share [%]</td>
<td>26.5</td>
<td>27.1</td>
<td>26.9</td>
<td>27.2</td>
<td>29.5</td>
</tr>
<tr>
<td>Social welfare reference network [€/km²]</td>
<td>201</td>
<td>201</td>
<td>334</td>
<td>334</td>
<td>557</td>
</tr>
<tr>
<td>Social welfare optimised network [€/km²]</td>
<td>-</td>
<td>222</td>
<td>353</td>
<td>355</td>
<td>577</td>
</tr>
</tbody>
</table>

* high weights

Figure 4 shows the differences for the results of the multi user-class model compared to those of the single user-class model. In general the differences are relatively small. The main exception is that in the multi user-class scenarios the optimal line spacing is larger, leading to slightly lower operational costs and to slightly longer travel times. Please note that the optimal frequencies remain identical. The larger travel times appear to be dominant, as social welfare is lower for all three scenarios. The patronage is highest in scenario 2 (high weights) while the operational costs in scenario 3 are lowest.
Figure 4: Relative differences for optimal networks for 3 alternative scenarios (single user-class is reference)

Just as in Section 2 the single user-class model based on the average traveller appears to be the best network design. It leads to the largest increase in social welfare, while the weighted travel times for both traveller groups are lowest. In scenario 2 the larger sensitivity for changes in the network for travellers having a car available leads to smaller changes in the network than scenario 1. The fact that in scenario 3 the difference in sensitivity between the two traveller groups is larger than in scenario 2 is more than compensated by the lower sensitivity of travellers without a car, which results in the largest differences compared to the single user-class model.

3.3.1 Conclusion

The main conclusion following from this analysis is that the more realistic specification of travel behaviour by distinguishing different traveller groups, does not lead to significant changes in the optimal network characteristics. The obvious differences in travel preferences between traveller groups are balanced by the size of the resulting patronage. Thus, for urban public transport network design it suffices to use a single user-class approach. This finding, however, does not imply that it is not necessary to analyse the network performance for different traveller groups. For a proper evaluation such network characteristics might still be very useful.
4 Conclusions

In urban public transport network design it is common to assume that all travellers behave identical, usually by using the characteristics of the average traveller. Travellers, however, clearly show different preferences towards public transport attributes. It is easy to distinguish traveller groups that are different in travel preferences. A typical example is the difference between travellers having a car available or not. Travellers having a car have relatively high weights for out-of-vehicle trip time elements, especially for waiting time, while travellers without a car available for the trip show lower weights for these trip time elements, except for access time. Given the interaction between network design and network usage, it is expected that distinguishing different traveller groups might lead to different network designs.

If public transport network design is focussed on specific traveller groups instead of the average traveller, the resulting optimal network characteristics appear clearly different. The optimal network for travellers having a car available is a coarse network having high frequencies, while the optimal network for travellers without a car available is less coarse and has lower frequencies. The analysis for an urban bus corridor shows two interesting findings. Firstly, the networks designed for travellers having a car available yield low values for the objective of social welfare. This is due to the fact that these travellers are not willing to accept long travel times, which reduces the value of the consumer surplus. Travellers without a car available are willing to accept relatively long travel times, leading to high values for the consumer surplus. Secondly, the network designed for the average traveller leads to the lowest weighted travel times for both traveller groups. The operational costs, however, are relatively high.

The traditional single user-class analytical public transport network design model is extended to a multi user-class model in which several traveller groups are considered simultaneously. Application of this newly developed extended model shows that distinguishing traveller groups leads to marginal changes in the optimal network design. The differences in preferences that determine the results of the scenarios for the single user-class analysis, are balanced by the size of the traveller group, or more precisely, by the size of the resulting patronage.

The main conclusion following from this analysis is that even though a multi user-class approach to urban public transport network design is preferable from a theoretical point of view, it does barely affect the optimal network characteristics. It appears therefore justified to use the traditional single user-class approach for urban public transport network design.

If the single user-class approach is used it is advisable to use the average traveller to describe travel preferences. Focussing on specific traveller groups does not necessarily lead to networks that are better suited for these travellers. In fact, due to the differences in travel preferences, the values for consumer surplus might be smaller or less sensitive for the quality of the services offered, leading to lower quality networks in terms of weighted travel times. Focussing on travellers having adequate...
consumer surplus and thus for social welfare for travellers without a car is substantially higher.
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