Modelling Multimodal Transit Networks

Integration of bus networks with walking and cycling

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Demand for (public) transportation is subject to dynamics affected by technological, spatial, societal and demographic aspects. The political environment, together with financial and spatial constraints limit the possibilities to address transit issues arising from growing demand through the construction of new infrastructure. Upgrading of existing services and improving integration over the entire trip chain are two options that can address these transport issues. However, transport planners and transport service operators often fail to include the entire trip when improving services, as improvement is normally achieved through the adaptations of characteristics (e.g. speeds, stop distances) of the services.

Our developed framework consists of two parts: one to assess the characteristics of the different bus services and their access and egress modes, and one to assess the effects of integration of these services, which includes the modelling and analysis in a regional transit model. The framework has successfully been applied to a case study showing that bus systems with higher frequencies and speeds can attract twice the amount of cyclists on the access and egress sides. It also shows that passengers accept longer access and egress distances with more positive characteristics of the bus service (higher speeds, higher frequencies).

Keywords—Bus network design; Cycling; Walking; Integration; Access Mode; Egress Mode

I.   Introduction

As transportation plays a crucial role in the establishment of economically strong regions and countries, a holistic systems approach for the analysis of transit systems is of high importance. Growing cities and changes in travel patterns have led to an increase in transport demand and distances travelled [1]. Although the construction of new infrastructure and transport links could increasingly meet this growing demand, financial, spatial and governmental aspects put constraints on the improvement of transit networks through the supply of new and costly infrastructure. Instead there is a need for the optimized use of existing services.

Transport planners and transport service operators often fail to include the entire trip when improving services, and thus create a gap between transport demand (from the passenger) and transport supply (services and infrastructure). Givoni and Banister [2] describe this mismatch between demand and supply. Where passengers (demand) make a choice of mode and network based on the overall journey, including access and egress modes, on the supply side the multi-modal aspect of trips and journeys is often overlooked by transit operators. Efficient transport systems can reduce costs in terms of travel times (passengers) and capacity (supply) meeting demand. Offering integrated transport services will reduce the costs and inconvenience of travel [3] for both the passenger and the supplier of transit services.

To help determine which characteristics of the entire trip influence choices of travellers, we have developed a framework. This framework allows for the comparison of different bus systems and helps in the decision making process when faced with possible public transport upgrades through the improvements of existing networks and services rather than through infrastructure upgrades. The objective of this paper is to present the framework developed by Brand [4] that assesses the integration of multi-modal bus networks, and to discuss the aspects and system characteristics that influence integration. These aspects follow from a case study in Stadsregio Amsterdam (City region of Amsterdam, now Vervoerregio).

II.   Integration in Transit Networks

A. Transport Network Integration

In this paper, integration is described as: 'the combination of individual elements (links) of the transport chain, from a travellers' origin to its destination, thus combining different transport networks in one system, with the aim to positively influence effects of the transport system. This combination involves the integration of the different links through improvement of mode specific characteristics that influence integration taking into account the environment of the entire system' [4].

The integrated bus system, under assessment in this paper, is presented in Figure 1 and consists of:

1. The Transport Chain
The transport chain is the entire trip from origin (O) through the access node (AN) and egress node (EN), using the bus link, to the destination (D).
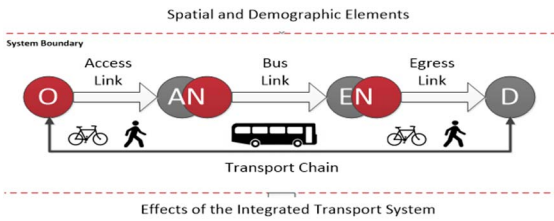
2. The Spatial and Demographic Elements
These are outside of the system boundary, and thus are elements from the environment of the system that influence the system.

3. The Effects of the Integrated Transport System
This is the 'outcome' of the system, the effects of the system on travellers (e.g. total travel time) and society (e.g. emissions).

The next paragraphs describe the different parts of the transport chain.

FIGURE 1: THE INTEGRATED TRANSPORT SYSTEM

B. Transport Chain Access and Egress: Walking and Cycling

Walking and cycling have a significantly smaller range than transit services. If the access and egress sides of transit, in terms of time or distances, exceed a certain threshold, a traveller will no longer opt to use the transit service [5]. However, at the ends of the trip (access and egress) walking and cycling allow for a high variety in options: both are not bound to spatial constraints. Krygsma et al. [5] identify walking and cycling as dominant access and egress modes and explain that these modes are sensitive to spatial characteristics (land use), environmental conditions (weather), and the travel distance. However, aspects of the public transport system also influence access and egress considerations, for instance waiting times at the public transport stop, in-vehicle times and prices. Krygsma et al. [5] also stress this: the catchment area of public transport networks also relies on the relative share of the total trip time, and not merely on the access and egress times. Shelat et al. [6] show that typical access distances are 1.5km (bus and tram) and 4 km. (train), With regard to egress these numbers are 0.7 km. and 2.7 km., respectively.

C. Transport Chain: Bus Links

Upgrading existing, hierarchically lower (conventional) bus services to high quality services, together with the consideration of the entire trip chain in the planning and control processes of public transport services could help improve existing services without the construction of new infrastructure. However, the upgrading of bus systems to high quality systems changes the performance of the total system. High Quality Bus Systems, or Bus Rapid Transit (BRT) essentially are bus systems higher in hierarchy than conventional systems, upgraded through network design (stop densities, speeds, line densities) and network service. Currie and Delbosc [7] identify the following improvements from conventional bus services to BRT services that can increase ridership:

- The higher frequency of bus services with longer operating hours;
- The bus priority systems (e.g. segregated right of way), which reduce journey times and improve service reliability;
- Improvement in the definition of networks and corridors, branding and information provision, which will ease the understanding of the system for the traveller.

III. DEVELOPING AN ASSESSMENT FRAMEWORK

With the assessment of transport network integration in literature and the description of the integrated transport system, several considerations can be identified that need to be captured in the framework:

1. The influence of network specific characteristics on transport network integration;

This implies that the framework should be able to identify and assess different characteristics of the system elements, and should be able to determine the influence of these characteristics on network integration.
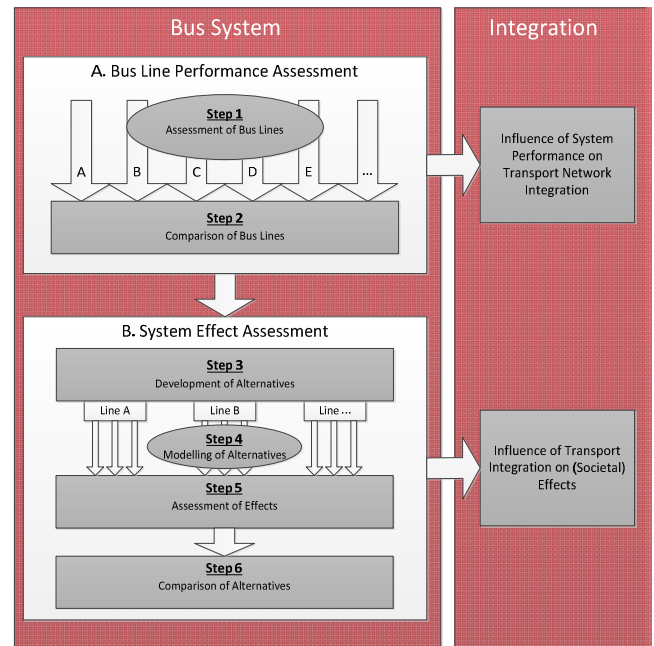
2. The influence of the integrated transport system on (societal) effects;

This implies that the framework should be able to determine the effects of a system, and should be able to determine the influence of network integration on these effects.

3. The assessment and comparison of different systems in terms of characteristics and effects.

This implies that the framework should allow for the comparison and improvement of different bus systems.

FIGURE 2: THE ASSESSMENT FRAMEWORK

The assessment framework needs to give insight in the characteristics of the identified elements (access, egress, bus, transfer, environmental) and their influence on integration. Furthermore, the effects of the integrated system need to be assessed in order to compare different systems (e.g. improved systems) to determine the influence of transport integration on these effects. As such, the framework needs to consist of two different parts:

1. **Bus Network Assessment**, which involves the assessment of different (types of) bus systems;
2. **Integration assessment**, which involves the assessment of the manifestation of integration in transport networks and the related integration effects.

The developed framework consists of two different parts, and to assess for performance and effects separately, two different steps in the framework need to be distinguished:

A. **Bus Line Performance Assessment**, which involves the assessment of different bus systems (bus lines), their elements and the characteristics of these elements.
B. **System Effect Assessment**, which involves the assessment of effects of (improved) integration of the individual systems, including a comparison between bus lines.

The considerations, the building blocks (elements and their characteristics) and the three different parts of the assessment framework lead to the framework that is presented in Figure 2.

A. Stadsregio Amsterdam

The developed assessment framework is tested using a case study, carried out for Stadsregio Amsterdam (now: Vervoerregio Amsterdam), being the public transport in the Amsterdam area. Stadsregio Amsterdam keeps on growing, in number of residents, workplaces and number of trips in the region. With a share of 43% of travellers from the Amsterdam region travelling to Amsterdam by public transport [8], and with an expected growth of 20% in public transport trips until 2025, there is a call for smart solutions to facilitate the growing number of trips. As such, Stadsregio Amsterdam has expressed the goal to facilitate more travellers in its network, offering a higher quality against lower costs, using targeted investments. The aim is to reach this goal by improving the use of existing facilities, networks and services, and hence improving the quality, reliability and travel times over the entire catchment area.

B. Public Transport in Amstelland-Meerlanden

This research is restricted to the concession area of Amstelland-Meerlanden, an area with different spatial levels (rural to urban levels) and a large network of both BRT and conventional bus lines [8]:

- Comfortnet: conventional bus lines, which are feeder lines to other, hierarchically higher, modes of transportation.
- R-Net: high quality, high speed bus services in the region around Amsterdam, connecting different cities, towns and villages in Amsterdam region, and connecting these areas with the city of Amsterdam. These are former conventional lines that have been upgraded.

Five Comfortnet lines and five R-Net lines are assessed using the developed integration assessment framework. To be able to assess the lines using the framework, data of these lines has to be gathered first. Three data sources are used as input: Zonal data (at Dutch post-code level) is gathered through the CBS (Central Bureau for Statistics), travel behaviour of passengers on the 10 lines is assessed using a survey and the performance of the bus systems is derived from GOVI data (Public Transport Information without Frontiers [9] . With this data, the first part of the framework (Bus Line Performance Assessment) is used to assess and compare the performance of the bus lines.

V.   CASE STUDY: RESULTS

A. Bus Line Performance Assessment

The bus line performance assessment as shown in Figure 2 consists of two steps. First the systems of different bus lines are assessed individually, based on a list of characteristics. Next, these bus lines are compared to determine which characteristics influence transport network integration. The following characteristics are included:

Environmental Elements	Level of urbanisation; Activities at a location (travel motive)
Access and Egress	The catchment area in time; The catchment area in distance; The mode choice for access and egress
Bus link	Physical network (stop density); Timetable assessment (reliability, frequency, service headway); Infrastructure (percentage of dedicated

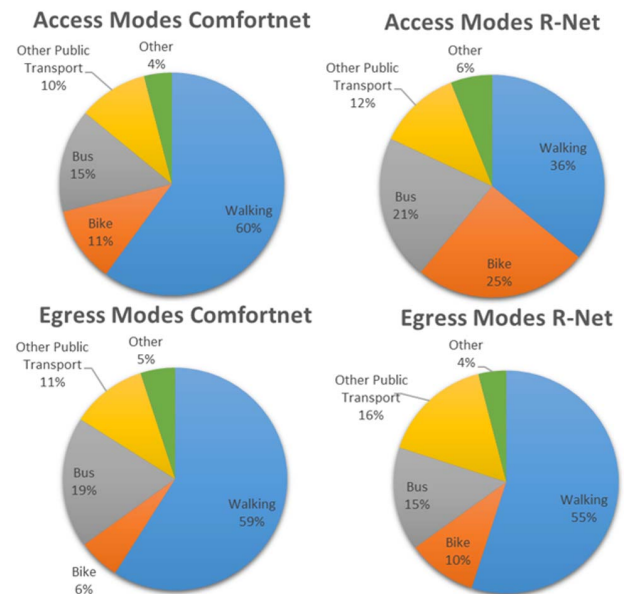|	infrastructure); Capacity of the line; Speed; In-vehicle time
Transfer Points	The waiting time at the bus stop; The usage of the bus stop

1)   Step 1: Assessment of Bus Lines

The different bus lines are assessed on elements and characteristics mentioned earlier, and are compared using a scorecard in step 2. General survey outcomes give an overview of system performance of the 10 assessed bus lines. The breakdown of use of access and egress modes for the bus lines is most important. The modal shares for access and egress of R-Net and Comfortnet are compared, presented in Figure 3

Figure 3 shows that the bicycle is an important modality on the access side, whereas its share on the egress side is much smaller. This can be explained by the fact that on the access side of a trip, people often have a bicycle at their disposal. On the egress side, bicycles are often not or less available. Furthermore, walking is more important on the egress side, suggesting distances on this side of the trip are often shorter, hence allowing for walking. When comparing the outcomes of the modal shares for the different bus systems, the bike has a more important position in R-Net trips as compared to Comfortnet trips. One explanation might be that people accept longer access and egress trips due to the (positive) bus trip aspects of R-Net (e.g. higher speeds, higher frequencies) as opposed to Comfortnet. Another striking observation from these figures is that for R-Net access walking has a relatively small share.

FIGURE 3: MODAL SPLITS FOR THE DIFFERENT BUS SYSTEMS

When comparing this to rail shares, similarities can be seen. For rail, research by Kennisinstituut voor Mobiliteitsbeleid [10] has shown that walking has a share of 24% on the access side, and 52% on the egress side. The bicycle has a share of 38% on the access side and 10% on the egress side. These shares indicate that people will travel shorter distances on the egress side, since the reach of a stop is smaller for walking. The share of walking is much lower on the access side than on the egress side. This leads to two explanations: people accept longer distances on the access side (walking has a low share), and on the egress side, people travel short distances, possibly due to the unavailability of other modes. These outcomes stress the importance of the bicycle on the access side, where for bus systems, walking and cycling are very often considered as one modality. Hence, it is important to consider cycling and walking as access and egress

modes separately to ensure integrated networks. Furthermore, the high use of the bus (Figure 3) on both the access and egress side suggest that other bus services are important as feeder services to faster or last-mile bus services. Opportunities might exist on the egress side of the trip (last-mile), for instance through the supply of cycle-hire facilities, thus aiming for competition between bus and bike for short last-mile distance.

2) Step 2: Comparison of Systems

The bus system (lines) are compared in three different ways: by bus type, by bus line, and by stop. The accepted distances for access and egress for walking and cycling have been assessed in more detail. Figure 4 shows the distances people have travelled for access by bike, together with the corresponding percentiles.

This figures show that for R-Net, distances travelled by bike on the access side are often higher than for Comfortnet. A larger catchment radius with a lower percentile indicates that a larger share of people are willing to travel larger distances. To give an example: in Figure 4, 40% of Comfortnet users travel up to 500 meters by bike to the bus stop, whereas for R-Net, 40% of the users travel up to 1000 meters by bike. Hence, it can be concluded that people travel longer distances by bike for R-Net as opposed to Comfortnet. For the egress side, this occurrence it not as apparent, which is explained by the low number of observed cycling trips on the egress side for both R-Net and Comfortnet. Figure 4 shows that the differences between R-Net and Comfortnet are not as apparent for walking as they are for cycling, to illustrate this, the 90th percentile has been marked in both figures.

Using the outcomes of the bus line comparison, relations that determine integration can be assessed. The following relations have been assessed using regression analysis:

- Stop density and catchment area (no significant relations)
- Speed of service and catchment area (significant relation for walking on the access side)
- Service frequency and catchment area (significant relation for walking)

The non-significance of walking on the egress side and cycling could be explained by the smaller number of observations for these links. The same holds for the non-significance of cycling in the frequency versus catchment area relation. With these relations, the catchment area can be determined using equations 1, 2 and 3.
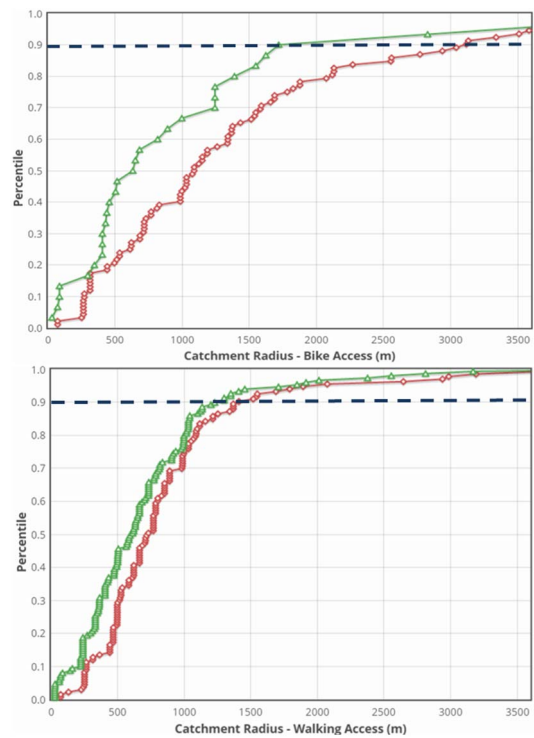
(1) Catchment area speed (access)	Where
Catchment (m)=0,269+0,011v	v=speed (km/h)
(2) Catchment area frequency (access)	f=service frequency (bus/h)
Catchment (m)=0,482+0,036f	
(3) Catchment area frequency (egress)	
Catchment (m)=0,459+0,023f	

Finally, the stop based comparison allows to consider elements from the environment that influence travel choice and integration. Three assessments have been conducted, being the assessment of spatial levels, the assessment of activities, and the assessment of type of bus stop (access or egress). A regression analysis has shown that there is a relation between the spatial level (1 for extremely urbanised, 5 for rarely urbanised) and the catchment area of the bus stop. The assessment of activities has shown no significant relations. This could be caused by the use of postal codes to assess activities. This more general zonal level

(instead of the more detailed postal code plus house number) results in rather large regions that can be assigned as 'residential', while there is a large educational facility that attracts the largest number of passengers. The final assessment, the type of bus stop, has shown that on the egress side for Comfortnet, walking distances are longer than for all Comfortnet stops (median). On the access side, both Comfortnet and R-Net have smaller distances than for stops that are not identified as dominant access stops.

The previous steps have shown that there is a relation between speed and catchment area and frequency and catchment area. This knowledge can be used to adapt existing bus lines to increase integration, which will be explained in the following steps of the framework.

FIGURE 4: CATCHMENT RADIUS FOR BUS BY BIKE AND FOOT (ACCESS)

B. System Effect Assessment

With the outcomes of the first step of the framework, insights are given into the characteristics that influence transport network integration. With this knowledge, the system can be adapted to increase integration. To do so, system effect assessment consists of four different steps. First, using the outcomes of the bus performance assessment, different alternatives for which characteristics are changed are developed. Next, these alternatives are tested in a modelling environment. The outcomes of these alternatives are then assessed and in the final step, these effects are compared for different bus systems.

Two different effects are tested using the modelling environment. These can be used in the final step (comparison).

1) The Total Travel Time

The total travel time is an important resistance factor of transport, and is calculated taking the sum of the access time, the waiting time, the in-vehicle time, the egress time and the hidden waiting time (at the origin). The valued time (VTC) of each of these travel time elements can be determined by multiplying the travel time with a factor. This multiplication is important, as Abrantes and Wardman [11] have found that time is valued differently in different parts of the trip. The in-vehicle time

factor is valued as one. The factors (multipliers) for the access and egress sides are 1.65, the multiplier for waiting time is 1.70 [11]. With these multipliers, the total travel time for the entire trip can be determined using equation 4.

(4) Travel Time	
$TT_{y,m}= \mu_a\, T_a+\mu_{wt}\, T_{wt}+T_{iv}+\mu_e\, T_e+T_h$	
Where	a=access
$TT_{y,m}$ is the total travel time of line y with modes am and em	wt=waiting time
	iv=in-vehicle
μ=multiplier per link type	e=egress
T=travel time per link type	h=hidden waiting time

2) Number of Passengers

When considering the number of passengers under the same environmental (spatial and demographic) circumstances, changes the total number of passengers using a certain bus line are the result of changes in characteristics (parameters) of the system elements. When more passengers in the same environment use a bus system, this suggests that the travel resistance has decreased. Hence, the total number of passengers is expected to increase with a better integrated system, since the resistance has decreased.

3) Step 3: Development of Alternatives

The previous steps have shown that two characteristics contribute to an increase in integration. For two bus lines in Amstelland-Meerlanden, one Comfortnet line and one R-Net line, alternatives are developed to determine the influence of the identified characteristics (integration) on the effects of the systems [4]. For the Comfortnet line, six alternatives are considered:

A. Base Alternative

B. Frequency Alternative	The frequency of the service is increased. For this alternative, the frequency is increased to 10 busses per hour (peak hour), in line with the frequency of the average R-Net line.
C. Speed Alternative	The commercial speed of the service is increased. For this increase, dedicated infrastructure is constructed in the modelling environment to minimise the influence of other traffic on the bus service.
D. Stop Density Alternative	Although no significant relation has been found between the stop density and the catchment area, this alternative is researched as an extra check. This alternative is modelled to see what would happen to the service if one of the characteristics of high quality services is imposed on the network.
E. Speed and Frequency Alternative	For this alternative, the frequency of the service is increased to 10 busses per hour, and the speed is increased to 30 kilometres per hour through the construction of dedicated infrastructure.
F Speed, Frequency and Stops Alternative	Three characteristics of high quality services are combined. Although stop distances do not influence the catchment area an increase in distances between stops does influence the speed.

For the R-Net line, three alternatives have been generated:

A. Base Alternative

B. Express Service Alterative	An extra bus line is added next to the existing R-Net service, creating an express service that connects the most important and strategically positioned stops on the line.
C. Speed Alternative	A tunnel could influence the speed. This alternative assesses the effect of increased speeds through the construction of a bus-only tunnel in the city centre of Haarlem, an area where the bus shares the road with other users.

4) Step 4: Modelling of Alternatives

The different alternatives are modelled and assessed using a transport model. The transport model used is the transit model of VENOM, the regional model of Stadsregio Amsterdam, using Omnitrans software [12]. The model has first been validated for use. By comparing the number of passengers, the modelled number of passengers, the model is validated based on outcomes. By comparing the usage of bus stops with the usage of bus stops in the model, the behaviour of the model is validated.

5) Step 5: Assessment of Effects

The different alternatives are modelled and compared [4]. This comparison allows for the calculation of total travel times, using the previously mentioned total travel time equation and the equations for the catchment area. This leads to total travel times per scenario, which will be used in a Cost-Benefit Analysis (CBA) in step six do determine the effects of the different alternatives.

TABLE 1: SOCIETAL COST-BENEFIT ANALYSIS

Comfort-net	Alternative	Travel Time (hh:mm)	Time gains/losses (hh:mm)	SCBA ratio (in €m)
	A	01:05		
	B	01:10	+ 00:05	+ 36,2
	C	00:57	- 00:08	+ 12,6
	D	01:08	+ 00:04	+ 0,3
	E	01:08	+ 00:04	- 0,3
	F	01:09	+ 00:05	- 69,8
	H	01:02	- 00:03	- 62,6
R-Net	**Alternative**	**Travel Time (hh:mm)**	**Time gains/losses (hh:mm)**	**SCBA ratio (in €m)**
	A	00:49		
	B	00:52	+ 00:03	+ 491,3
	C	00:52	+ 00:03	+ 5,4

Table 1 shows the differences in total travel time (average per passenger) for the different alternatives compared to the base. This table shows that for R-Net improvements, the perceived travel times increase, hence there is no benefit from improvements in terms of travel times. For Comfortnet improvements, several alternatives show a decrease in travel times experienced (including waiting time). Given that the distance travelled in the bus is the same for all alternatives, a decrease in in-vehicle time has been observed (due to increased speeds), but the access and egress times do not decrease. As such, passengers seem to accept a longer access and egress time if the characteristics of the bus system (speed, frequency) positively influence the in-vehicle and waiting times.

6) Step 6: Comparison of Systems

The performance of the different alternatives, in terms of travel time and number of passengers, is done using a Societal Cost-Benefit Analysis (SCBA). This SCBA allows to assess the alternatives on societal viability by taking into account both the costs of implementation of these alternatives (e.g. operational costs, implementation costs), as well as the benefits (travel time

savings, increase in operational income through the increase in number of passengers). This analysis shows (see Table 2) that the frequency alternative for the Comfortnet line is feasible (has the largest positive Cost-Benefit ratio), as is the tunnel alternative for the R-Net line. The large differences in cost-benefit rations between the different alternatives could be explained by the use of a multiplier for access and egress time, in combination with the fact that the accepted access and egress distances (catchment, and thus times) increase with more positive characteristics of the bus service (higher speeds, higher frequencies). This results in longer travel times, although they seem to be accepted by the passengers. Why this happens could be explained either by the use of the multiplier [11], which is probably too high. Other explanations could be found in the travel behaviour of passengers, but this goes beyond the scope of this research.

VI. CONCLUSIONS

This paper presented and demonstrated a new methodology of assessment of integration in bus networks, the combination of the bike and buses in a transport trip, and the influence of integration of the effects of a bus system. The framework consists of two parts, one to assess the characteristics of the different bus services and their access and egress modes, and one to assess the effects of integration of these services with access and egress modes.

With the developed framework, several bus lines have been assessed in the area Amstelland-Meerlanden of Stadsregio Amsterdam. The assessment has shown that R-Net (Dutch BRT system), which has a higher frequency and speed than Comfortnet (conventional bus service) can attract twice the amount of cyclists on the access and egress side. Passengers of bus services are prepared to travel longer distances when bus services are more frequent and/or have higher speeds. As such, the assessment of bus lines has shown that passengers not only take the service quality into consideration for public transport choices, but also include access and egress part of the trip chain in their decisions.

The bicycle is an important modality on the access side, whereas its share on the egress side is much smaller. This can be explained by the fact that on the access side of a trip, people often have more modes at their disposal, and thus have a larger choice of modes. On the egress side, these modes are often not or less available. The combination of cycling and bus networks, something which has not been research extensively yet, proves to provide opportunities for transport planners. There is an opportunity to increase the share of the bicycle on the access side to bus networks (in particular BRT) by providing parking facilities at the bus stop, and opportunities on the egress side by providing bike-sharing and bike-renting opportunities.

The developed assessment framework can be used as a method to assess and compare different bus lines based on their performance and integration with access and egress modes. With the framework, integration can be assessed, both by the analysis of different characteristics of the different bus lines, as well as by the comparison of different bus lines belonging to different types of bus services (e.g. conventional lines and high quality lines). Furthermore, the framework allows gain a deeper understanding of integration, by not only analysing characteristics responsible for integration, but by also assessing

the effects of altering these characteristics to allow for improved integration in the entire trip chain. As such, the framework is capable of assessing and identifying characteristics responsible for integration, as well as assessing the effects of the transport system. Apart from these scientific contributions of the framework, it is also useful for public transport authorities and operators to assess the performance of their bus systems, and to evaluate which characteristics could be improved in order to create a positive SCBA outcome that benefits both the authority as well as the passenger.

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