Measuring public transport and built environment integration at the neighborhood scale

Towards a quantitative assessment methodology

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Abstract

Public transport and built environment integration at the neighborhood scale is an important aspect of land use transport integration. Public transport systems and the built environment affect each other in a multitude of ways at the neighborhood level. These mutual effects impact the quality and performance of both systems; whether the outcome is positive or negative depends on how carefully they are attuned to each other – or in other words, how well they are integrated. Yet despite this importance, there are only few attempts to quantitatively define and measure integration at the neighborhood scale. Existing approaches have limitations, most importantly, they lack a clear theoretical framework of what exactly should be measured. To fill this research gap, a new approach to identify quantitative indicators for integration at the neighborhood scale is presented. It is based on the systematic analysis of mutual interactions between public transport systems and the built environment and the subsequent identification of measuring points.

1 Introduction

Achieving a sustainable urban future is one of the great challenges of our time, particularly because the majority of people already live in cities today and urbanization is rapidly increasing in many parts of the world (Puppim de Oliveira et al. 2012, DESA 2015). In this context, land use and transport integration are a crucial factor (Brommelstroet and Bertolini 2010, Yigitcanlar and Kamruzzaman 2014). Its importance stems from the fact that mobility plays a pivotal role in urban sustainability (e.g., it affects emissions, energy consumption, opportunities in daily life, economic prosperity, and quality of life (Jenks, Williams, and Burton 2000, Goldman and Gorham 2006, Cheng, Bertolini, and le Clercq 2007, Hull 2011, Bertolini 2012)), and that mobility patterns and travel behavior are strongly intertwined with the way cities are built – the form and structure of the built environment (BE). Land use patterns and urban structures influence travel behavior and thus transport flows, mode choice and travel times, but these in turn define accessibilities and therefore determine location choices and – again – land use patterns (Mackett 1985, Handy 2005, Chang 2006, Næss 2006, Ewing and Cervero 2010). Consequently, transport and land use integration is incorporated in many planning policies worldwide (Burchell, Listokin, and Galley 2000, Curtis and Punter 2004, May, Kelly, and Shepherd 2006, German EU Presidency 2007, Waddell 2011).

Public transport (PT) is frequently presented as a key factor for achieving integrated transport and land use – commonly in combination with compact and mixed-use urban development (Devereux, van der Bijl, and Radbone 2005, Kenworthy 2006, Curtis and Scheurer 2010, Suzuki, Cervero, and Iuchi 2013). One main reason for this is that PT bundles movements and is therefore much more space efficient and creates less emissions than car travel, which is particularly valuable where densities are high and space is scarce. On the other hand, “mass transit needs mass” (Suzuki, Cervero, and Iuchi 2013, 15), i.e., is not viable without a certain conglomeration of users (density), and mixed uses tend to generate a more evenly distributed demand which allows for greater efficiency of PT (Suzuki, Cervero, and Iuchi 2013, Orth, Frei, and Weidmann 2015). Therefore, PT only works efficiently if the BE is aligned to its needs, but it can also contribute to a better quality of the BE if such coordination is achieved. In fact, the interactions between PT and BE are multitudinous.

There are many concepts and planning approaches geared towards PT and BE integration, such as eco-city (Roseland 1997, Kenworthy 2006), new urbanism (Katz 1994, Leccese, McCormick, and Congress for the New Urbanism 2000), sustainable accessibility (Bertolini, le Clercq, and Kapoen 2005, Curtis 2008), pôle d'échanges (Menerault 2006), smart growth (Burchell, Listokin, and Galley 2000, Downs 2005, Handy 2005), and transit-oriented development (TOD) (Calthorpe 1993, Cervero et al. 2004, Dunphy et al. 2004, Curtis, Renne, and Bertolini 2009). However, their implementation is not always successful and planning reality deviates strongly from what would be adequate given the theoretical knowledge developed. While institutional barriers and unsuitable planning practices play a role (Curtis 2008, Brommelstroet and Bertolini 2010, Switzer, Bertolini, and Grin 2013), another important reason is the lack of objective assessment approaches for PT and BE integration (Renne and Wells 2005, Evans and Pratt 2007, Dur, Yigitcanlar, and Bunker 2014, Hale 2014).

In recent years, this problem has been addressed on a regional scale with the development of quantitative accessibility-based approaches for PT and BE integration (Bertolini 1999, Cheng, Bertolini, and le Clercq 2007, Curtis and Scheurer 2010, Kamruzzaman et al. 2014, Singh et al. 2014, Papa and Bertolini 2015, Vale 2015). They allow for systematic assessment and comparison at the regional scale, and incorporate many of the interactions between PT and BE.

However, there are also important interactions at the neighborhood scale, which are not adequately considered by these approaches. For example, detailed density distribution relative to PT stop location influences PT patronage; location and mix of uses influence PT demand distribution; and road space organization such as pedestrian crossings, street layout, and segregation type affect PT performance (Currie, Ahern, and Delbosc 2011, Carrasco, Fink, and Weidmann 2012). Because PT supply is spatially discrete, access and egress legs are prerequisites for any ridership at all; walking and (to a lesser extent) cycling are the main modes for access and egress, and their attractiveness and competitiveness depends on the structure, quality and safety of the urban environment, on local activity range, as well as on the provision of designated infrastructure (Loutzenheiser 1997, Filion, McSpurren, and Appleby 2006, Carmona et al. 2010, Adkins et al. 2012). PT operation, layout, and design in turn affect local quality aspects of the BE such as accessibility, legibility, permeability, noise, and safety (Burns 2005, Devereux, van der Bijl, and Radbone 2005, COST TU1103 2015, Marti et al. 2016). Yet despite the importance of the neighborhood scale, there are only few attempts to assess PT and BE integration at this level, and those that exist have important limitations.

This paper addresses this research gap and presents a new approach for measuring neighborhood-scale PT and BE integration. It is structured as follows: Section 2 explains why neighborhood-scale PT and BE integration is beneficial, why it should be assessed, and who could be interested to assess it. Furthermore, it derives requirements for such an assessment, analyzes existing approaches, and identifies an important gap in research and practice. Section 3 presents the proposed approach. Section 4 ends with conclusions and an outlook on future research.

2 Quantitative assessment of neighborhood-scale public transport and built environment integration

2.1 The case for neighborhood-scale PT and BE integration

2.1.1 Defining PT and BE integration

According to the Oxford Dictionaries (Oxford University Press 2016), “integration” refers to “the action or process of integrating”, which in turn means to “combine (one thing) with another to form a whole”. Obviously, PT and BE always form some kind of a whole, because they are present within the same space. In the context of land use and transport, “integration” therefore normally includes the notion of coordination and quality – it means to combine the two systems in such a way that the best possible overall outcome is achieved.

As shown in section 1, there are various interactions between PT and BE. So the configuration of PT relative to the configuration of BE affects – among other things – the BE’s quality; and the same holds for the reverse direction. However, the quality of both PT and BE are influenced by many more factors. But since integration is concerned with their combination and the outcome thereof, what is of interest here are beneficial and adverse mutual impacts between the two systems when they are combined. Simply put, to achieve the above mentioned best possible overall outcome for both PT and BE, each system needs to be in service of the other.

Based on these considerations, the following definition of integration was developed:

Integration of PT and BE is achieved if their constitutive elements are attuned to each other in a way which reinforces positive and mitigates negative mutual influences between the two systems as much as possible under given conditions.

2.1.2 The benefits of PT and BE integration

The core benefit of integration is apparent given the considerations and the definition above. By attuning BE and PT to each other, a mutually beneficial union between them can be formed. This means that synergies between the two systems are activated and a situation can be achieved which is better (for the combined system PT and BE) than any that could be achieved by only focusing on PT or BE outcomes.

In practice, the unidirectional optimization of PT or BE – or even just one specific aspect thereof – is quite common since domains are normally separated organizationally and the expertise required to address PT and BE issues differs substantially. Such a unidirectional approach may lead to a good overall result (meaning for the combined system PT and BE), but it may also not. Even if both PT and BE are optimized simultaneously, but each based on their own specific set of goals, the combination is still rather random since their configuration is not adapted to each other. Of course they *may* be well attuned to each other in such a case, but only accidentally, since there is no systematic consideration of the mutual effects. Therefore, they may also be very badly attuned to each other, leading to a bad outcome for the combined system PT and BE.

Contrary, the outcome of this combined system can be systematically improved by taking the way in which PT and BE affect each other into account explicitly – in other words, by considering integration between BE and PT as a goal.

The benefits of PT and BE integration are thus primarily on a subordinate level, where the overall effects of the combined system PT and BE are considered. That is why PT and BE integration is often a goal in overall planning or development policies as part of an overall land use transportation integration (see section 1). But there are benefits of considering integration also for individual actors in BE and PT, as will be shown in the next section.

2.1.3 PT and BE integration assessment

If PT and BE integration is considered a worthwhile goal, it is crucial to be able to assess the degree to which it is achieved. Only the operationalization of the concept of integration in such an assessment allows to purposefully pursue integration. Without such an assessment, it is not possible to evaluate whether integration is good or bad in a given situation, or to compare situations relative to their integration performance.

There are many potential scenarios in which an integration assessment could be used.

Table 1 structures them into four generic use cases.

Table 1: Potential application scenarios for PT and BE integration assessment

Application		Explanation
Prospective	Comparison of alternatives	Deciding which alternative performs best with regard to integration, typically in project development where integration is one of the project goals; e.g., this could be the case for large scale settlement projects on former industrial plots, for a LRT line extension, or for a strategic development plan of a municipality. Even without alternatives to compare, suitability of a specific project could be evaluated using benchmark values from other, similar cases.
	Identification of potential improvements	Finding ways to improve integration by identifying strengths and weaknesses with regard to integration (both spatially and topically). Such an analysis can support idea generation, e.g. designing interventions to improve integration, or inform the setting of priorities.
Retrospective	Success evaluation	For already executed projects with explicit integration goals, ex-post analysis can be used to evaluate how successfully these goals have been achieved.
	Theoretical analysis	Identification of factors that are generally decisive for integration by comparing results for different cases.

Interpretation of PT and BE integration assessment results depends on the perspective or the questions asked: Both changes in PT and BE could improve integration. For example, the implementation of a new PT project or the adaption of a PT system can greatly enhance integration, but also densification of underused areas around a PT stop or improvements of the pedestrian network can have beneficial integration effects.

2.1.4 Who has an interest in PT and BE integration assessment?

There are two different levels of interest in applying integration assessment. First, any actor that actively promotes, demands, encourages, or pursues PT and BE integration needs to assess how well integration is achieved at some point. The most typical case would be a government agency responsible for spatial development, for example within a city or municipality, a regional entity, or even at national level. Such an actor might be interested in all of the four application scenarios for integration assessment mentioned in

Table 1. It needs to compare alternatives if it is actively involved in planning an integrated project, or if it evaluates different alternatives proposed by another party. In the case of active planning, it may use the assessment of the status quo to generate ideas for improving integration. If it has funded or executed projects with integration as a goal in the past, it needs to evaluate their success to learn for the future. And since it is interested in how to improve integration in general, insights on what affects the integration performance of the combined system PT and BE most would also be of high interest.

Second, any actor pursuing its own goals within the context of PT or BE development may also benefit from using integration assessment at some point. This could be, for example, a PT agency or a real estate developer. It could be that a project such an actor is working on is within a regulatory framework that demands or incentivizes PT and BE integration. In such a case, the actor does not necessarily have a direct motivation to achieve integration, but it needs to include it as an explicit goal to meet policy requirements. Another possibility is that integration assessment may help one actor to achieve its goals by creating and highlighting synergies with other actors. Integration assessment facilitates finding solutions that are beneficial for both the respective actor and one or several other parties, which makes said solution easier to implement because these other parties also have an interest in the project. Or it may even expand the project boundaries, because another actor can be convinced that changing something within its control has beneficial effects for it. Such an expansion of the solution space potentially allows for solutions that are better for the specific actor than any alternative that lies solely within its own control.

It is important to note that integration assessment does not simply combine goals from different perspectives or actors in the context of PT and BE. Rather, it evaluates specifically how well PT and BE are attuned to each other. That means that the explicit consideration of integration as a goal (and its evaluation using integration assessment) does not replace other goals. For example, a PT operator would still want to evaluate predicted patronage of a new PT line (with its tool of choice, e.g. a direct demand model), even if it also assessed integration. Integration assessment would include an evaluation of how well the configuration of the BE (such as density distribution and pedestrian network) supports PT demand as one of many performance measures, but it would not predict that demand (because demand also depends on many factors beyond integration). Another example, a real estate developer would still want to evaluate prospective rents or sales revenues (for example with a hedonic pricing model), even if it used integration assessment. The latter would evaluate the effect of PT on the attractiveness of a neighbourhood or project, but it would not predict profit prospects (because there are many influences on real estate prices beyond the way PT is geared towards the BE).

In the end, there will always be a combination of goals, of which integration is only one. However, only the explicit consideration of integration and its assessment render it even possible to include it in an evaluation and weight it according to stakeholders' preferences.

2.1.5 The neighbourhood scale

As shown in section 1, PT and BE integration assessment has mainly focused on accessibility so far. It is typically evaluated at a regional scale, while various interactions between PT and BE are located at the neighborhood scale. Theoretically, accessibility tools could capture some of the local effects, such as footpath configuration impacts on PT access and egress, but this would require very fine-grained analysis – often unrealistic given the regional scope of analysis. Furthermore, other local effects are not related to accessibility, such as BE configuration effects on PT safety and reliability or PT alignment and operation effects on BE permeability. Thus, integration assessment needs to consider these neighborhood-scale effects explicitly, otherwise it disregards important interactions between PT and BE, rendering an incomplete evaluation of their integration. Furthermore, the regional scope of accessibility analysis means that it requires data over a large area. If the focus of integration assessment is on one specific neighborhood, e.g. for a new master plan or a bus line extension, it might be necessary to evaluate the project only based on the project perimeter.

Therefore, a method for PT and BE integration assessment focused on the neighborhood-scale is needed to complement accessibility-based, regional-scale approaches.

2.1.6 Examples of planning situations where neighbourhood-scale PT and BE integration assessment is needed

2.1.6.1 Example 1: Integrated local long-term development plan

Local long-term development plans for transport and land use often include the stated goal of PT and BE integration. One reason for this could be incentives – for example, the Swiss Federal government's agglomeration programs (ARE 2015) co-fund local infrastructure projects, but demand that they are derived from an integrated vision of development, including settlement, transport, and landscape. Therefore, PT and BE integration is an important goal that local stakeholders consider when working on such plans, and they need to assess its achievement. Furthermore, in order to develop projects in the frame of such a plan, they could use an integration assessment of the current situation to identify how integration could be improved and derive projects from this analysis – strengthening their argument towards funding.

2.1.6.2 Example 2: Planning of a tram line extension

In most cases, planning of a tram line extension would be primarily dealt with by the PT operator or a local or regional PT agency. Such an actor would typically consider potential demand (e.g., patronage based on where activities are and where they are expected to be in the future, demand patterns due to uses within the influence areas of stops), the reliability and speed of the service (e.g. due to interactions with other road users, alignment, and design), and system safety. It might also analyze whether access and egress paths for pedestrians are adequate, and consider this in the position of stops or try to improve the existing network (e.g. in cooperation with local authorities or in negotiations with property owners or developers). It might create a set of route alternatives and compare them relative to their outcome in such goals. The best alternative would therefore maximize patronage, level out demand peaks, consider reliability and speed, and optimize access for potential users.

But there would be no explicit consideration of how the BE is affected by the tram line extension. For example, it might cut the settlement apart, creating detours for pedestrians and cyclists. Changes in overall accessibility for residents may be distributed unequally. The new line might, or might not, contribute to the identity of the community it serves or passes through. It likely would affect local traffic in some way, which in turn might affect local congestion and transport emissions.

If integration were included as an explicit goal, attuning the extension so it affects the BE in the best possible way would complement the other goals of the planning actor stated above. Of course, considering these effects complicates matters for the planning actor. In some cases, what is good for most PT goals might not render the best result for integration, and vice versa. So there is little inherent incentive to include integration in this planning task if the sole interest is to achieve the best result for PT. However, PT is not a purpose in itself. It serves people, and it is normally a heavily subsidized and thus partially public good. Its purpose goes beyond patronage and operational quality, although those are obviously indicators for attractive service and overall success. Thus, its effect on the BE should be considered. Furthermore, such a project needs support from various other actors: It might need funding approval, it might need local support in a referendum, it might require the collaboration of developers or land owners, or it might require investment by the local authorities. Any actor primarily interested in the BE is much easier convinced if the project is integrated in that it also explicitly considers how it affects the BE. Last but not least, taking into account effects on the BE might also inspire solutions that include changes within the realm of another actor – fostering collaboration and possibly enabling an outcome which is also better for the PT actor than any solution which only considers changes in its own area of responsibility.

2.1.6.3 Example 3: Master plan for redevelopment of large former industrial site

An investor developing a former industrial site using a master plan would very likely consider mobility and accessibility as important topics. For example, how do people access and egress the site in different modes? What kind of uses are possible and profitable given the location relative to transport networks and other uses? Which parts of the site are best reachable with public transport? But a developer would not necessarily consider how the development affects PT – how the proposed uses would affect demand patterns, whether there is enough density to sustain the PT supply needed to serve the site attractively, whether the planned density distribution is geared towards PT stop locations, whether pedestrian paths between building sites and PT stops are direct, or how the design would affect PT reliability, speed, and safety.

In this case, there is some inherent interest to ensure attractive PT, since it is an important factor for site attractiveness and can affect real estate value. Also, in many policy contexts, integration of settlement and public transport development is a requirement for project approval. Furthermore, again, such a project requires the collaboration of many partners, also from the PT domain. Convincing them would be considerably easier if the project explicitly considers effects on PT.

2.2 Requirements

As shown in the previous section, neighborhood-scale PT and BE integration assessment has benefits and is therefore a worthwhile endeavor. The considerations above also imply certain requirements for such an assessment; they are elaborated below.

<u>Focus on integration</u>

Integration assessment should assess how well PT and BE are integrated. Given the definition of PT and BE integration in section 2.1.1 and the subsequent elaboration of its merits, this means that integration assessment needs to focus on how PT and BE affect each other. If it assesses anything else, it confounds topics, since that means it actually (also) evaluates other goals than integration.

<u>Clear rationale for included aspects</u>

Any aspect included in an integration assessment should be derived from the above consideration, i.e., it should reflect how PT and BE affect each other.

<u>Comprehensive consideration of interactions between BE and PT</u>

An integration assessment approach must comprehensively cover interactions between BE and PT. If it fails to do so, it does not fully capture how well PT and BE are integrated.

<u>Create an assessment output</u>

In order to be usable, integration assessment needs to create some form of output which enables either a comparison of how good integration is in different situations or an absolute valuation of integration performance.

Consideration of context

Since integration is a generic concept, its assessment in specific situations needs to account for the respective context, for example by including adaptable parameters or by comparison to benchmarks that are adapted to the specific application case.

Adequate granularity

The aspects considered in integration assessment must be considered as fine-grained as feasible in order to capture small-scale effects.

Based on neighborhood data

The assessment needs to be based primarily on data or information from the specific analysis area, i.e. the neighborhood that is being assessed. If larger-scale aspects are considered, they should not be dominant, i.e., an assessment should be possible even if they are not available.

2.3 Existing approaches

Given the considerations in 2.1.5, there is need for an integration assessment approach systematically considering interactions between PT and BE at the neighborhood scale to complement existing accessibility-based approaches that focus on the regional scale. Currently, such an approach is missing.

There are, however, studies that consider certain aspects of PT and BE integration at the neighborhood scale. They are mostly concerned about qualifying TOD in some way – creating TOD typologies, differentiating TOD from transit-adjacent development, evaluating TOD success, or assessing the extent to which a project or an area holds TOD characteristics.

While they might be ideally suited for their stated purpose, they each only assess PT and BE integration at the neighborhood scale partially.

Schlossberg and Brown (2004) compare and rank 11 TOD sites with walkability indicators using three techniques: network classification, pedestrian catchment areas, and impedance-based intersection intensities. Thus, they focus on one specific aspect of integration (walking access).

Renne and Wells (2005) identify and evaluate indicators for measuring impacts of TOD and propose ten indicators most useful for this purpose based on expert opinion and data availability. Their system of indicators was not operationalized. Linked to them, Evans and Pratt (2007) propose a list of indicators based on the results of Renne and Wells (2005) and further literature, related to the categories travel behavior, built environment, economic, social diversity and quality. Again, their indicator set has not been operationalized. In both cases, the focus was not on integration assessment, but rather TOD classification.

Renne (2009) introduces a spectrum for the differentiation between transit-adjacent development (TAD) and transit-oriented development (TOD) based on characteristics of station precinct. The application of the TAD-TOD spectrum to case studies in the San Francisco Bay Area used a mixture of quantitative (e.g., density, mix of uses, mode share, street links, nodes, block dimensions) and qualitative measures (rating of station design, pedestrian and bicycle accessibility). For the latter, a point scale is used, but the study falls short of defining how exactly the assessment of qualitative criteria should be conducted. Furthermore, since the measures are focused on station precinct characteristics, PT characteristics are not considered with the same level of detail as the BE.

Hale (2014) proposes the metric of "sustainable mode share" as leading indicator for transport success in TOD; furthermore, he suggests that the same metric can distinguish between "genuine TOD" and TAD (transit-adjacent development) by means of a fixed threshold of 50% sustainable mode share. This approach is focused on one aspect of integration (sustainable mode share) and not adaptable to context due to its fixed threshold.

Dur, Yigitcanlar, and Bunker (2014) develop a spatial index for measuring neighborhood-level land-use and transport integration. They use 24 indicators in categories transport (accessibility, mobility), urban form (density and diversity, design and layout), and externalities (pollution, resource consumption). These cover a broad range of aspects linked to neighborhood sustainability that go beyond integration; this particularly concerns indicators of the category "externalities" (e.g., storm water quality). Furthermore, the indicators are not adapted to context (for example, their density indicator renders always the same result for the same value, regardless of the context such as an urban or suburban setting).

The TOD Standard (ITDP 2014) proposes a set of 21 indicators for eight principles of TOD, namely attractive and safe walking, attractive and safe cycling, connected walking and cycling networks with direct links, high-quality PT, use mix, high densities, compact development, and reducing space for cars. The system can be used to assess either projects or station areas. It comprehensively covers the aspects most commonly attributed to TOD and includes metrics that are easy to compute and include comparison with benchmark values (adaptable to context), which is in line with its goals. However, this is also the reason that its scope is larger than PT and BE integration and is generally directed at crating livable and vibrant neighborhoods around high-quality PT, and that some of the metrics are simplistic. For example, density is not considered relative to the location within a station area (i.e. distance to a stop).

The approaches listed above generally do not analyze interactions between PT and BE systematically and therefore do not provide a thorough theoretical framework to identify what exactly should be measured in an integration assessment and why. Particularly, effects of the BE on PT are not widely considered, with the focus being on effects of PT on the BE, mixed with other effects within the BE itself. Listing these shortcomings is not a critique of these approaches – none of them have the stated purpose of assessing PT and BE integration at the neighborhood scale. However, they are the approaches found in literature that come closest to doing exactly that. The fact that none of them fulfils the requirements set out in section 2.2 demonstrates a research gap: the development of an approach for measuring neighborhood-scale PT and BE integration that fulfils these requirements, particularly to be based on a clear rationale for what exactly should be measured.

3 Proposed approach for measuring neighborhood-scale public transport and built environment integration

3.1 Scope

The approach for measuring neighborhood-scale PT and BE integration presented in this paper addresses the research gap identified above and aims to fulfil all the requirements set out in section 2.2. However, its scope is limited in two ways: first, it is focused on the physical environment, and second, it only enables integration assessment for concrete combinations of PT and BE.

For the first point, it is important to understand that PT and BE integration is often analyzed in terms of outcomes, for example modal split or indicators for BE quality such as real estate prices. Such outcomes do not only depend on the physical configuration of BE and PT, but also on aspects such as policies, culture, legal frameworks, and most notably on people's behavior and choices. The latter in turn depend not only on what happens within a specific neighborhood (for which behavior is observed), but also on what lies beyond – particularly accessibility with different modes. The approach presented here focuses on what is physically "observable" in a neighborhood, i.e. how PT and BE are configured (this applies to existing situations, but can also be used for concrete proposals or plans for changes in PT systems or the BE). Assessing how well the configurations of PT and BE are attuned to each other – referred to as integration assessment above – is thus not necessarily enough to judge whether the effects that are commonly desired from PT and BE integration are actually taking place and to what extent. Rather, it examines whether the configuration of BE and PT in a specific neighborhood provide the *potential* to achieve such outcomes. This is also why the proposed approach does not predict any outcomes; instead, it focuses entirely on how well attuned the physical configuration of PT and BE are to each other.

The second point refers to two possible approaches to PT and BE integration assessment. The first one is of generic, explorative nature. Its goal is to evaluate the PT orientation of the BE based on indicators such as density, land use diversity, or walkability. An example is the "potential TOD index" by Singh et al. (2014), which attempts to identify locations where "development's characteristics […] are ripe for use of transit" (Singh et al. 2014, 130), but current PT connectivity is poor – which could inform decisions about the focus of future PT improvements. The second approach assesses situations where PT already exists or is planned – it is therefore focused on concrete combinations of BE and PT. Thus, it can incorporate measures that explicitly assess how well the two are coordinated. For example, instead of simply using the density of an area as an indicator, its distribution relative to the location of PT stops or the co-location of certain uses with PT stops could be considered. The assessment method presented in this paper is based on the second approach. Therefore, its goal is the integration assessment of concrete combinations of PT and BE (be they real or planned / proposed).

3.2 Approach overview

The approach developed consists of three linked parts. First, a diagram of the constitutive elements of PT and BE and of interactions between them is developed, based on influences reported in literature. In a second step, this system elements diagram is used to identify measuring points for integration. Third, quantitative indicators are developed for each of these measuring points. These indicators can then be used for integration assessment. They measure the magnitude of the input of positive and negative mutual effects between PT and BE, and do not predict the outcome of any elements within the system elements diagram.

In the following sections, system elements diagram, measuring point identification, and indicator development are explained in more detail.

3.3 System elements diagram

Due to the importance of interrelations between elements of PT and the BE discussed in section 2, those elements and the effects between them were analyzed as a base for the proposed integration assessment approach. The goal was to systematically identify all mutual interactions between PT and BE that are related to the neighborhood scale, and to structure them clearly for further analysis. To achieve this, a system elements diagram has been developed based on the literature – essentially a graphical representation of all relevant elements (boxed) and interactions between them (arrows). It is of qualitative nature, i.e. it only depicts whether or not there is some kind of interaction between two elements, but does not quantify that interaction.

The structure of the system elements diagram consists of three parts: (i) there are two "domains", PT and BE; (ii) each of the two domains is structured into four thematic sectors that also represent scale levels; (iii) elements are attributed to one of four types. This structure is depicted in Figure 1.

The four thematic sectors for the BE are location, public space/road section, neighborhood, and city/region. For PT, they are stop, section, line, and network. In both PT and BE domains, the last thematic sector (depicted at the top in Figure 1) represents elements beyond the neighborhood scale that have important interactions with elements within the neighborhood scale. The four element types are input elements, which are considered as external influences and cannot be altered, for example by planning decisions; points of influence, which represent possible intervention points; variable elements, which are affected by other elements but cannot be directly influenced; and results, which represent the outcome of the two domains PT and BE. Influences between elements are either within a domain or across domains. Influences are only considered within the same element type layer and across layers in the direction from input to results. While secondary effects in the other direction exist in the long term (and might influence input elements, such as creating a shift in the sociodemographic characteristics of inhabitants in a specific area), they are not present when analyzing one specific "snapshot" of a concrete combination of PT and BE and are therefore beyond the scope of this paper.

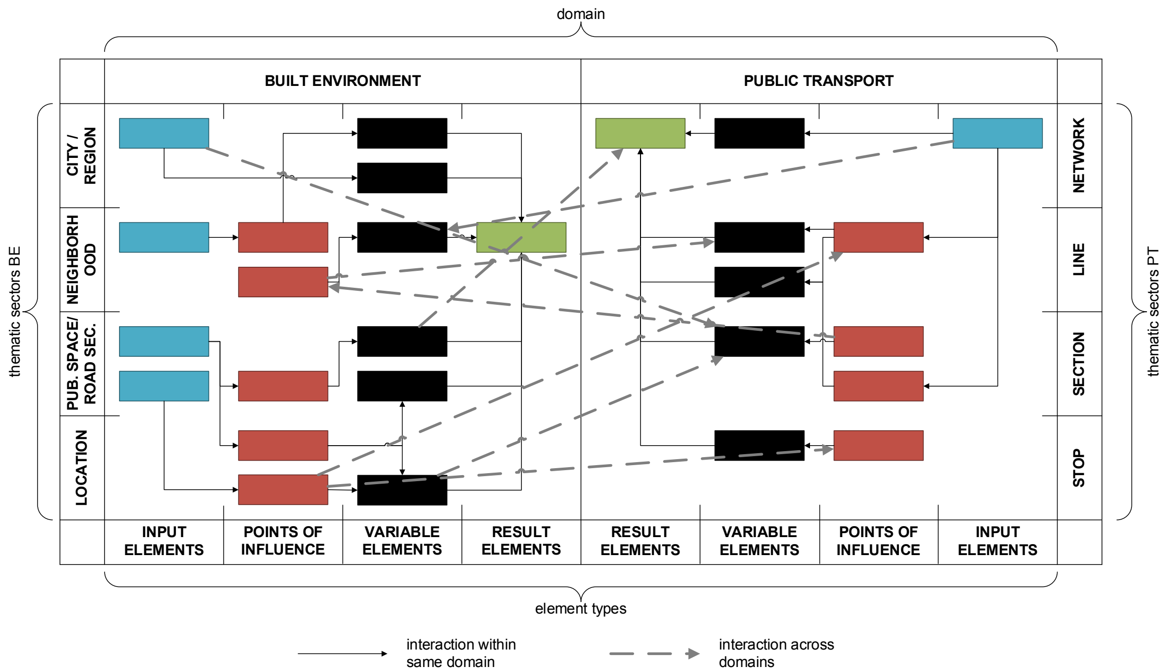

Figure 1: Structure of the system elements diagram; colors reflect system element types

The elements included in the system elements diagram were defined based on a literature review, starting at result elements of both PT and BE and tracing influences and respective elements backwards. This review started from one result element each for PT and BE: PT productivity and BE attractiveness. They are influenced by variable elements, which in turn are influenced by other variable elements, points of influence, and input elements. All the elements and interrelations included in the system element diagram are listed in tabular form with respective literature sources in Appendix II. Due to its size with 64 elements and 183 influences, the entire system elements diagram cannot be depicted graphically at once. However, Appendix I contains diagram excerpts which in combination represent the entire diagram.

3.4 Measuring point identification

The purpose of the system elements diagram is to identify what should be measured to assess PT and BE integration at the neighborhood scale. As argued in section 2, integration is based on mutual effects. In the network of influences within the diagram, there are many ways in which BE affects PT and vice versa. In order to analyze these mutual influences systematically, effect chains starting from the two result elements PT productivity and BE attractiveness are analyzed. Since these effect chains are very complex due to the size of the system elements diagram, they are analyzed separately for every element that directly influences one of the two result elements. This effect chain analyses are based on system elements diagram excerpts that include all elements which directly or indirectly influence the starting point of the analysis.

Since only mutual effects between PT and BE are of interest here, solely the effect chains starting from an element which itself is influenced directly or indirectly by at least one element of the other diagram domain (PT / BE) are further considered. Figure 2 depicts all system elements which directly influence one of the two result elements, and highlights those elements that are further considered as starting points for effect chain analysis. For better readability, Figure 2 only includes direct influences on result elements and omits influences between the depicted variable elements.

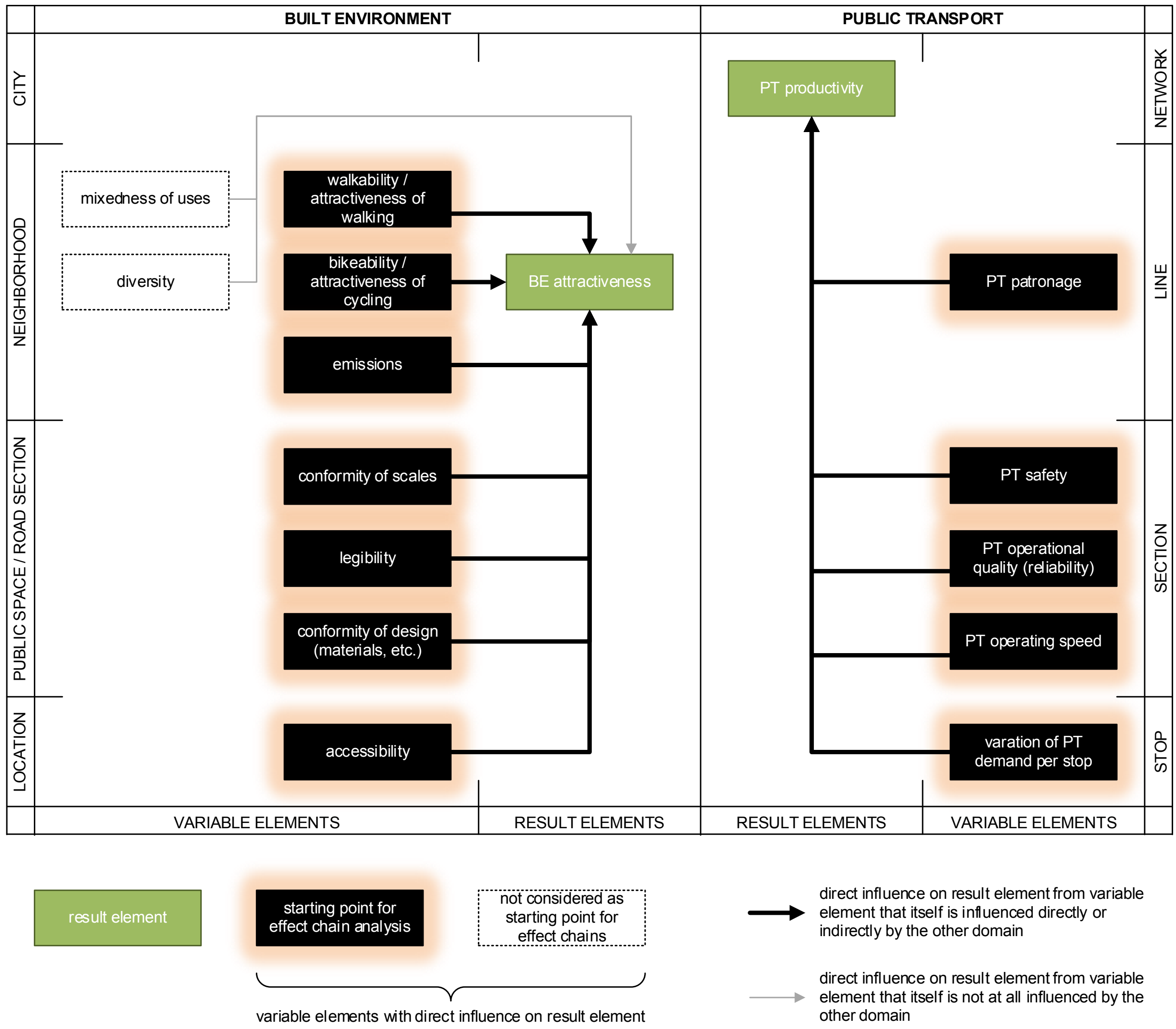

Figure 2: Excerpt of system elements diagram showing all elements that directly influence result elements, direct influences on result elements, and starting points for effect chain analyses with diagram excerpts; note that the figure excludes influences between the variable elements

The diagram excerpts for all the elements highlighted in Figure 2 are included in Appendix I.

As an example, Figure 3 contains the diagram excerpt for PT safety.

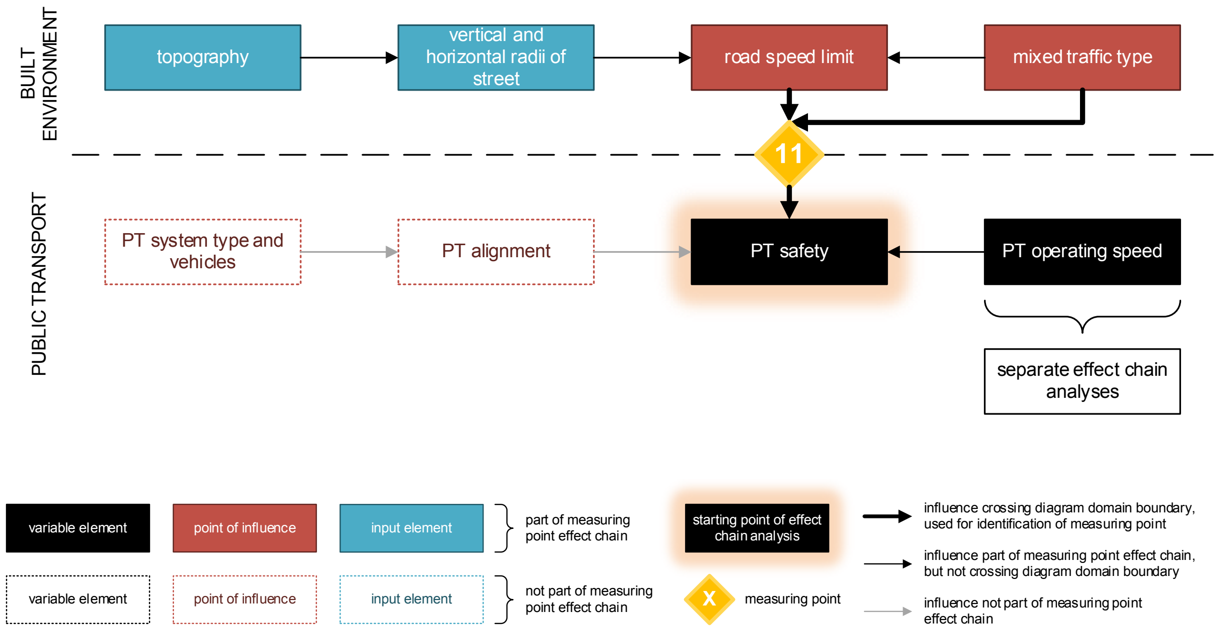

Figure 3: System elements diagram excerpt for effect chain analysis on PT safety

In these diagram excerpts, all influences that cross the diagram domain boundary indicate potential measuring points for integration. However, such domain-crossing influences that originate at input elements (which are considered as unalterable in the context of this research) are not further considered, since they do not depend on the way in which PT and BE are combined, but rather on the context in which this happens – and this context is not what should be measured. Influences that are the base for a measuring point are highlighted in the system elements diagram excerpts. All measuring points are listed in Appendix III.

In the example PT safety (Figure 3), there are two elements of the BE that directly affect PT safety: road speed limit and mixed traffic type. The latter furthermore affects the former, which is additionally influenced by road geometry and topography. Also, PT safety is affected by the alignment of PT systems, which in turn is influenced by the type of PT system and vehicles. Also, PT operating speed affects PT safety, and is itself influenced by many other elements. However, this element is itself highlighted in Figure 2, which means it is the starting point of a separate effect chain analysis (see Figure 15 in Appendix I). Thus, influences on PT operating speed are not further analyzed in the effect chain analysis on PT safety. If needed, they can be extracted from Figure 15. One measuring point (numbered 11) has been identified in Figure 3: the influence of mixed traffic type and road speed limit on PT safety. This example also shows again the scope of the proposed approach: PT safety does not *only* depend on mixed traffic type and road speed limit, it might even mainly depend on other factors (particularly of the PT system itself). However, these two BE elements do affect PT safety according to literature, and are mutual influences between BE and PT – therefore, they are what should be measured when assessing PT and BE integration.

3.5 Indicator development

For each measuring point identified in the system elements diagram, a quantitative indicator is developed. The indicators should quantify the magnitude of the input of positive and negative mutual effects in order to assess how well elements of PT and BE are attuned to each other. To achieve this, the direct influence at the measuring points and further indirect influences are examined in the respective system elements diagram excerpt and possible variables for indicators identified. Additionally, previous indicators and measuring approaches for the same or similar influence(s) are considered based on a literature review and advantages and disadvantages of options are evaluated.

A key element of indicator development is to define what is "good" and "bad" for each measuring point, i.e., what outcome for the "receiving" system element of the considered cross-domain interaction is beneficial or adverse for the respective domain (PT or BE). This definition is based on literature (in most cases, the sources given in Appendix II include the necessary information) or direct logical derivation. Subsequently, input values of the elements affecting this "receiving" system element need to be linked to these outcomes. Thus, the assessment is based on the value of the affecting elements, instead of focusing on the (possibly unknown and/or confounded) outcome of the "receiving" element (see section 3.1). This is crucial, because this outcome is very likely affected by more than the quality of PT and BE integration (see for example Connor et al. (2006)), and therefore its assessment would not be focused only on integration assessment.

The goal in indicator development is to create a measure that is both holistic and feasible, i.e., does not oversimplify the influences concerned and is as fine-grained as possible (see section 2.2), but at the same time, is not unnecessarily complicated and relies on data that is available with high probability for different contexts. Furthermore, since indicators are supposed to be applicable based on observations within the area of interest (see section 2.2), the variables included need to reflect this. For a discussion on the fine thread between soundness and plainness of measurement, see Bertolini, le Clercq, and Kapoen (2005).

Indicators need to account for context (see section 2.2). This is achieved by creating a formulation that covers the respective influences generically, but includes adaptable parameters where adequate. These parameters need to be estimated for concrete application, for example based on context-specific studies, national standards, or benchmark values of comparable cases.

Indicators are normalized to values between zero and one, and they are of increasing form, i.e., higher values represent a better integration. Indicators are aggregated to an index; however, it is crucial to be able to consider individual indicator results in the assessment, since they point to strengths and weaknesses of a case. Indicator and index results for one single case are not meaningful as such – only in comparison to either other alternatives, different cases, or benchmark values can they be interpreted as “good” or “bad”.

3.6 Indicator overview

Indicators have been developed for each of the measuring points listed in Appendix III, based on the literature as described in section 3.5. They are listed in Table 2, including a brief description of what is considered positive or negative for the “receiving” element, which elements in the system elements diagram affect this outcome most, the analysis scale, and how their values are linked to the qualification of the outcome.

Table 2: Indicator overview

Ind.	Property	Description
1A Influence of PT on pedestrian permeability of the BE		
	Positive / negative outcome	Permeability of the BE is an important influence on walkability and BE quality and thus positive; it is mainly captured by connectivity, defined as "quantity of the connections in the network and thus the directness and multiplicity of routes through the network" (Tal and Handy 2012, 48-49).
	Affecting elements	PT can separate two sides of its alignment and thus reduce permeability; magnitude of effect depends on PT alignment, operating speed, and frequency.
	Analysis scale	PT section
	Proposed measure	Impedance that PT infrastructure and operation inflict on pedestrians crossing the PT section at any location along it, compared to a situation without presence of PT; using average detour and average crossing waiting times due to PT.
1B Influence of PT on bicycle permeability of the BE		
	Positive / negative outcome	As for walking, permeability plays an important role for cycling, because connectivity affects directness of routes, which in turn affects journey time (one of the main determinants of bicycles use). Therefore, permeability is positive.
	Affecting elements	See 1A
	Analysis scale	PT section
	Proposed measure	Impedance that PT infrastructure and operation inflict on cyclists crossing the PT section while following routes on the bicycle network, compared to a situation without presence of PT; using average detour and average crossing waiting times due to PT.

2 Influence of PT on distribution of public and road space		
	Positive / negative outcome	Space used for transportation decreases public space for other uses that can increase BE attractiveness. Depending on circumstances, dedicated PT space can increase or decrease overall transport space. In any case, it should be utilized efficiently. Therefore, the amount of space PT consumes should be in line with the service offered and higher efficiency is better.
	Affecting elements	PT alignment (in turn affected by PT system type and vehicles) defines how much public space PT uses.
	Analysis scale	PT section
	Proposed measure	Dedicated area for PT relative to section length and capacity provided.
3 Influence of PT on car traffic volumes		
	Positive / negative outcome	High car traffic volumes have an overall negative impact on BE attractiveness.
	Affecting elements	PT attractiveness affects PT modes share, which in turn can affect car traffic volumes in a neighborhood. PT attractiveness is affected by most elements of PT, particularly supply (service characteristics), comfort, reliability, speed, safety, and access quality. The first two of these are largely within the control of PT, whereas the rest depend heavily on the BE and other aspects. Thus, analysis focuses on supply and comfort.
	Analysis scale	Neighborhood
	Proposed measure	Two subindicators: average supply characteristics (frequency, service regularity, service time span) and comfort (stop design, vehicles) in neighborhood compared to benchmark values (for similar density of neighborhood).
4 Influence of PT on conformity of scales of the BE		
	Positive / negative outcome	If the scale of a PT system deviates from the surrounding BE in a way which makes PT appear dominant, the quality of the BE can be severely affected.
	Affecting elements	The scale of a PT system mainly depends on the infrastructure (PT alignment) and the PT system type (which defines vehicles and also affects alignment).
	Analysis scale	PT section
	Proposed measure	Qualitative scale conformity score (vehicles and section separately)

5 Influence of PT on legibility of the BE	
Positive / negative outcome	A PT system can contribute to the legibility of the BE, particularly by providing reference points and recognizability.
Affecting elements	The contribution of PT to BE legibility depends mainly on the type of PT alignment, the system type (also affects alignment), and stop design.
Analysis scale	PT section / PT stop
Proposed measure	Qualitative legibility score (section and stops separately)
6 Influence of PT on conformity of design of the BE	
Positive / negative outcome	Conformity of a PT system with the design of the BE is important for embedding it and creating a visually and spatially coherent environment.
Affecting elements	Design conformity of PT depends on infrastructure (alignment, system type) and stop design.
Analysis scale	PT section / PT stops
Proposed measure	Qualitative design conformity score (section and stops separately)
7 Influence of PT on accessibility	
Positive / negative outcome	Higher accessibility increases the attractiveness of a location for almost every possible activity, including residential, commercial, and public uses, and is thus desirable.
Affecting elements	Overall accessibility is affected by PT accessibility, i.e. the access PT provides for locations within the analysis neighborhood to all activities within the city / region. This is in turn affected by the overall PT network, PT speed and supply, and the position of PT stops.
Analysis scale	City / region
Proposed measure	Public transport accessibility metric

8 Influence of BE on PT mode share		
	Positive / negative outcome	High mode share for PT has positive effect on PT in most cases. Other modes (car, walking, and cycling) can compete with PT or complement it. On average, cars tend to compete with PT, while both walking and cycling complement it.
	Affecting elements	Generally, car-orientation of BE negatively affects PT mode share directly (higher attractiveness of cars) and indirectly (attractive PT supply less feasible; walking and cycling impractical and unattractive); main impacts on car-orientation are the distribution of public space and local accessibility (of services, jobs, etc.).
	Analysis scale	neighborhood
	Proposed measure	Two subindicators: space designated for human powered mobility in overall circulation space for cars, walking, and cycling; local accessibility metric.
9 Influence of BE on PT access quality		
	Positive / negative outcome	The quality of access and egress to and from PT stops is an important factor of PT attractiveness. From a PT perspective the most relevant question is how easy it is for pedestrians and cyclists to reach PT.
	Affecting elements	For walking, route directness and pedestrian network completeness are the key influences on access/egress attractiveness. For cycling, they are route directness and bike-friendliness of the network.
	Analysis scale	PT stop influence area
	Proposed measure	Weighted average detour factor for access or egress from/to closest PT stop from/to all activities, considering only specified pedestrian network (walking) and accounting for bike-friendliness of bike network (cycling).
10 Influence of BE on number of activities with access to PT		
	Positive / negative outcome	The number of activities with access to PT influences PT patronage – thus the higher the number of activities with access, the better.
	Affecting elements	Absolute density within PT stop influence area defines maximum number of potential users. Willingness to walk/cycle to or from PT decays with increasing access or egress distance, thus density distribution relative to PT stop location strongly affects probability of actual PT use.
	Analysis scale	PT stop influence area
	Proposed measure	Two subindicators: comparison of average density in PT stop influence area with benchmark value (comparable situations); density distribution assessment based on notion that density should be equal or higher at a point located closer to PT stop than at one further away.

11 Influence of BE on PT safety		
	Positive / negative outcome	Safety is a factor of PT attractiveness and affects productivity; Thus, a higher PT safety level is desirable.
	Affecting elements	PT safety is strongly affected by interactions with other road users, which in turn are influenced by the layout of the BE, particularly mixed traffic type, street and intersection layout and operation, priority measures for PT, and car traffic speed.
	Analysis scale	PT section
	Proposed measure	Share of segregated, partially segregated, and mixed operation in PT section length, share of protected intersections (relative to traffic speed).
12 Influence of BE on PT reliability		
	Positive / negative outcome	Reliability is a central factor of PT attractiveness and affects productivity; thus, better PT reliability is desirable.
	Affecting elements	As safety, reliability is strongly affected by interactions with other road uses; elements see indicator 11.
	Analysis scale	PT section
	Proposed measure	Share of priority operation (any form of unobstructed operation) in section length, number of interactions in priority sections per type (e.g. pedestrian crossings, unprotected / protected),
13 Influence of BE on PT max. speed		
	Positive / negative outcome	Maximum PT speed affects PT operating speed, which is important for PT attractiveness and for productivity (see indicator 14). Thus, higher maximum PT speed is desirable.
	Affecting elements	If PT is affected by other road users, maximum PT speed depends on road speed limit.
	Analysis scale	PT section
	Proposed measure	In sections where PT is affected by other road users: road speed limit.
14 Influence of BE on PT operating speed		
	Positive / negative outcome	Speed is a central factor of PT attractiveness and affects productivity; thus, higher PT speed is desirable.
	Affecting elements	As safety and reliability, operating speed is strongly affected by interactions with other road uses; elements see indicator 11.
	Analysis scale	PT section
	Proposed measure	Operating speed due to BE impacts compared to unaffected operating speed.

15 Influence of BE on variation of PT demand per stop	
Positive / negative outcome	A smooth temporal (low demand peaks) and directional (bi-directional demand) demand pattern increases the efficiency of PT and is thus positive.
Affecting elements	PT demand patterns for a PT stop are mainly affected by the type and mixedness of uses within the influence area of that stop.
Analysis scale	PT stop influence area
Proposed measure	Ratio between population and jobs for a PT stop influence area.

3.7 Are requirements met?

The proposed approach was developed to fulfil all the requirements set out in section 2.2. The following paragraphs illustrate how each of the requirements is met.

<u>Focus on integration</u>

Since the identification of measuring points is based on the systematic analysis of mutual interactions between PT and BE in the system elements diagram, each indicator concerns one aspect of how well PT and BE are attuned to each other. Indicators evaluate influences based on the affecting elements, and do not predict or measure the outcome of the affected element. This is because this outcome is influenced by more than the quality of PT and BE integration, and thus its evaluation or prediction would confound the assessment, i.e. it would actually include more than integration.

<u>Clear rationale for included aspects</u>

Each indicator is derived from a measuring point which in turn is identified following a clearly defined procedure of analyzing the elements of PT and BE and the interactions between them. Furthermore, the indicator development follows the same approach in each case, by analyzing which outcome of the affected element is considered positive or negative in literature, linking the state of affecting elements to these outcomes, and developing the indicator to assess the magnitude of this influence based on the state of the affecting elements.

Comprehensive consideration of interactions between BE and PT

The system elements diagram used to systematically identify measuring points is based on a broad literature review on relevant elements and interactions between them, ensuring a comprehensive coverage of aspects relevant for integration in the indicator set.

Create an assessment output

The development of an indicator set allows comparative assessment of integration quality and the identification of strengths and weaknesses of each case.

Consideration of context

Generic indicator formulation using adaptable parameters which are estimated based on context ensures adaptability to case-specific circumstances.

Adequate granularity

The indicators developed consider small-scale effects and are thus adequate for neighborhood-scale assessment.

Based on neighborhood data

Indicator development is directed at using data which is based on the state of the relevant system elements within the area of interest, i.e., the neighborhood to be assessed.

4 Conclusions

The main question underlying this article is: What should be measured when assessing neighborhood-scale PT and BE integration? Or, in other words, how can indicators for neighborhood-scale PT and BE integration be identified based on a clear theoretical framework? This question matters because integration at the neighborhood scale affects the quality and performance of both BE and PT, and its assessment is necessary to purposefully pursue integration and thus activate synergies. Yet, no previous approach has thoroughly answered the questions above.

Starting from a definition of integration and the discussion of its benefits and the merits of its assessment, this article derives requirements for integration assessment and highlights gaps in existing approaches. The main contribution is a new approach for the development of an indicator system for neighborhood-scale PT and BE integration that closes this gap and fulfils the requirements set out. Through the systematic analysis of interactions between PT and BE, it ensures that indicators only measure integration, while at the same time covering all aspects of this integration comprehensively. An important distinction is that indicators evaluate the magnitude of influences based on the affecting elements and do not predict the outcome of the affected elements. This is because these outcomes are also affected by other aspects than PT and BE integration, and thus their prediction would either be inaccurate if solely based on integration or the indicators would need to assess further aspects and therefore not focus on integration.

In future research, the set of indicators presented in this article will be applied to case studies in different contexts. The results will be used by an expert panel for the development of interventions aiming at better integration – and the adapted situations evaluated again using the indicators. This application will shed light on the validity and usefulness of the developed indicator set. Furthermore, application in different contexts will reveal whether the indicators are really of generic nature, i.e. whether they are universally applicable with only an adaption of parameters.

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7 Appendix I: System elements diagram excerpts

Figures 4 – 16 depict the system elements diagram excerpts used for effect chain analysis starting from all elements highlighted in Figure 2. For an explanation of graphical elements used, see Figure 3.

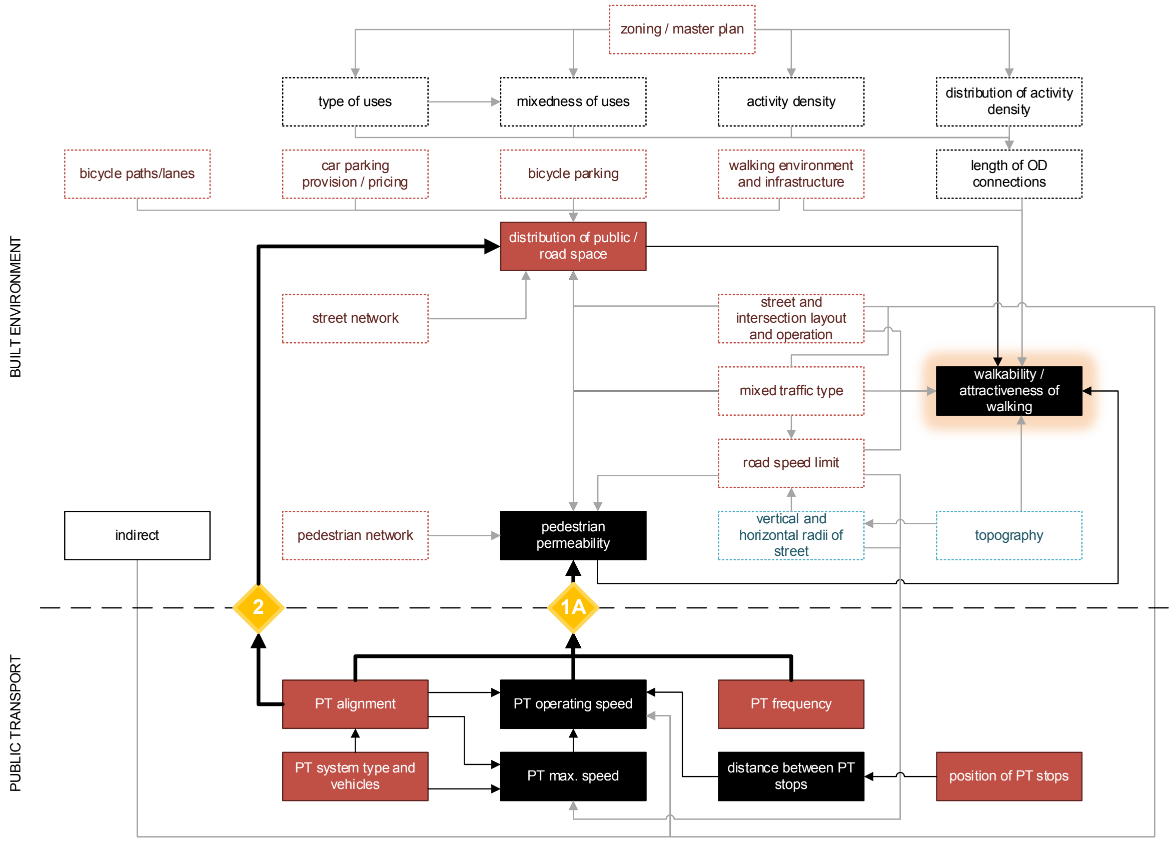

Figure 4: System elements diagram excerpt for effect chain analysis on walkability

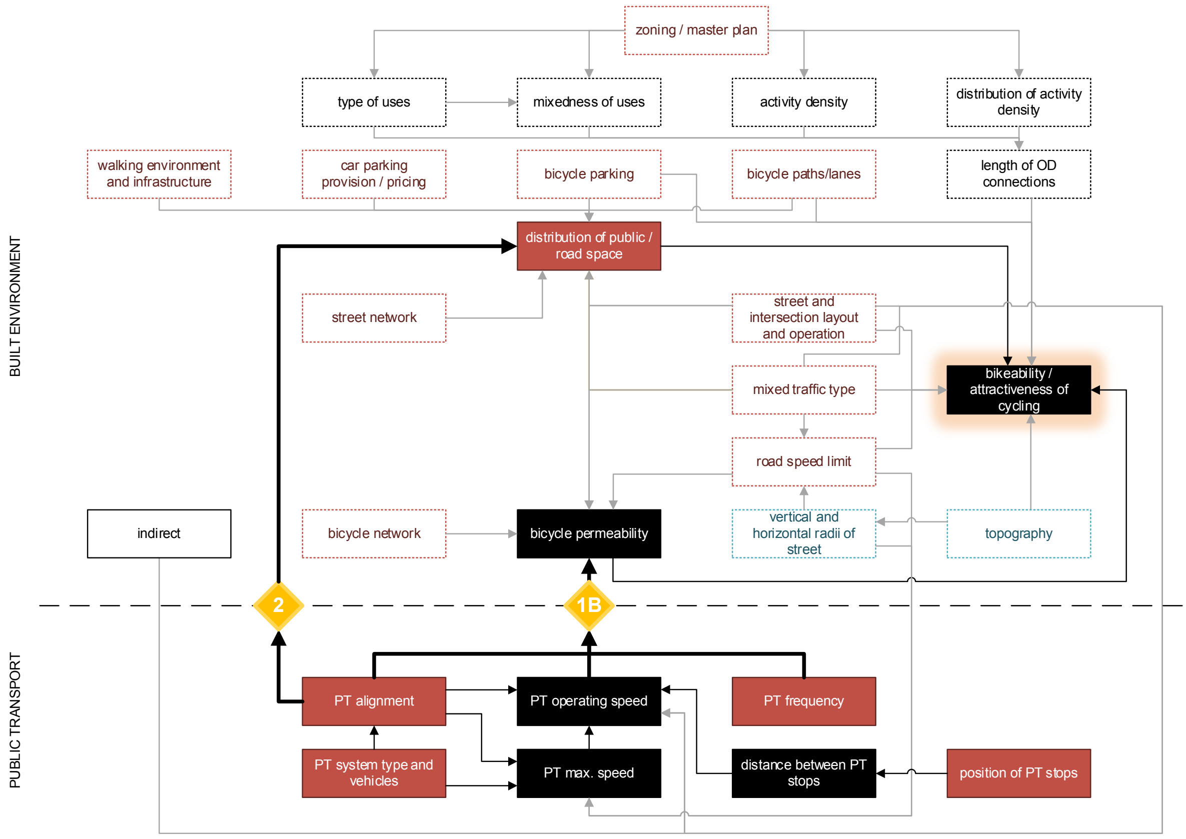

Figure 5: System elements diagram excerpt for effect chain analysis on bikeability

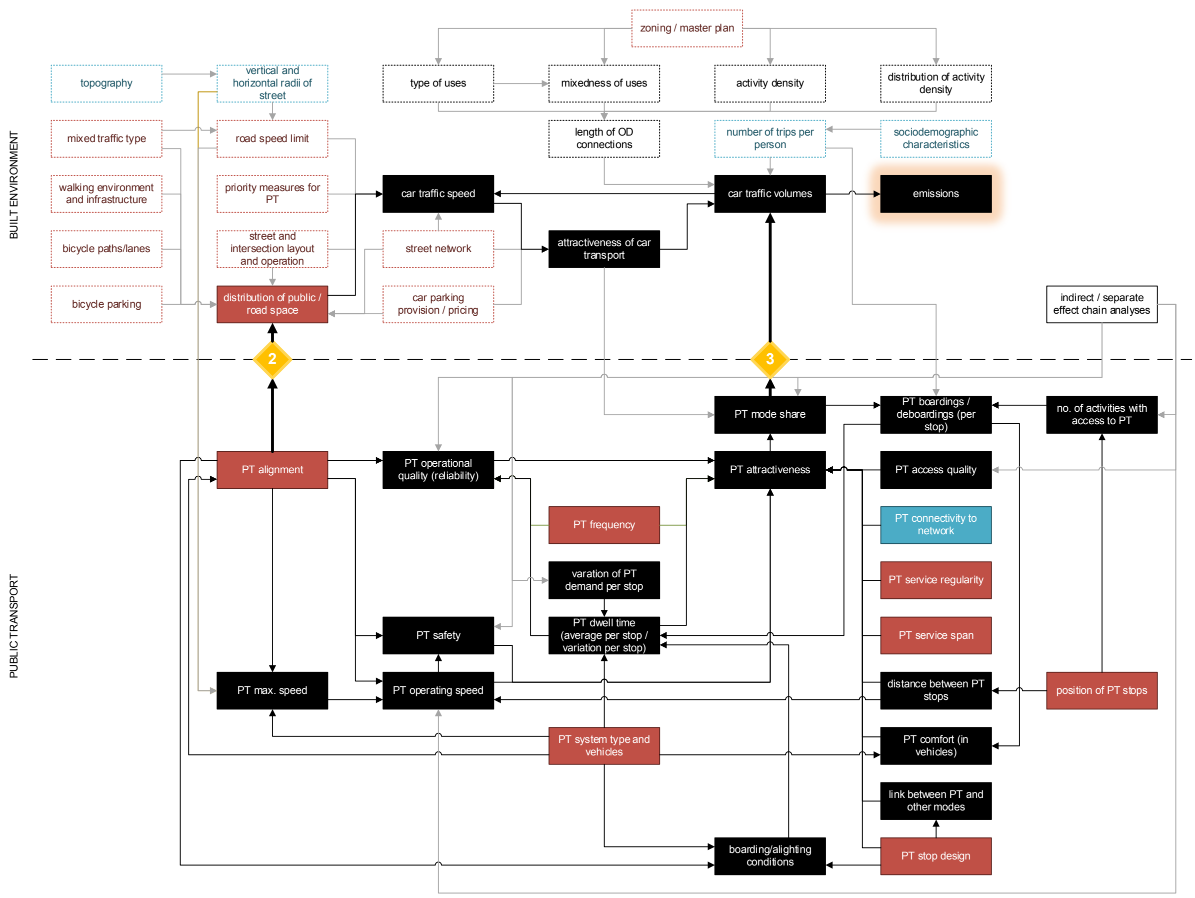

Figure 6: System elements diagram excerpt for effect chain analysis on emissions

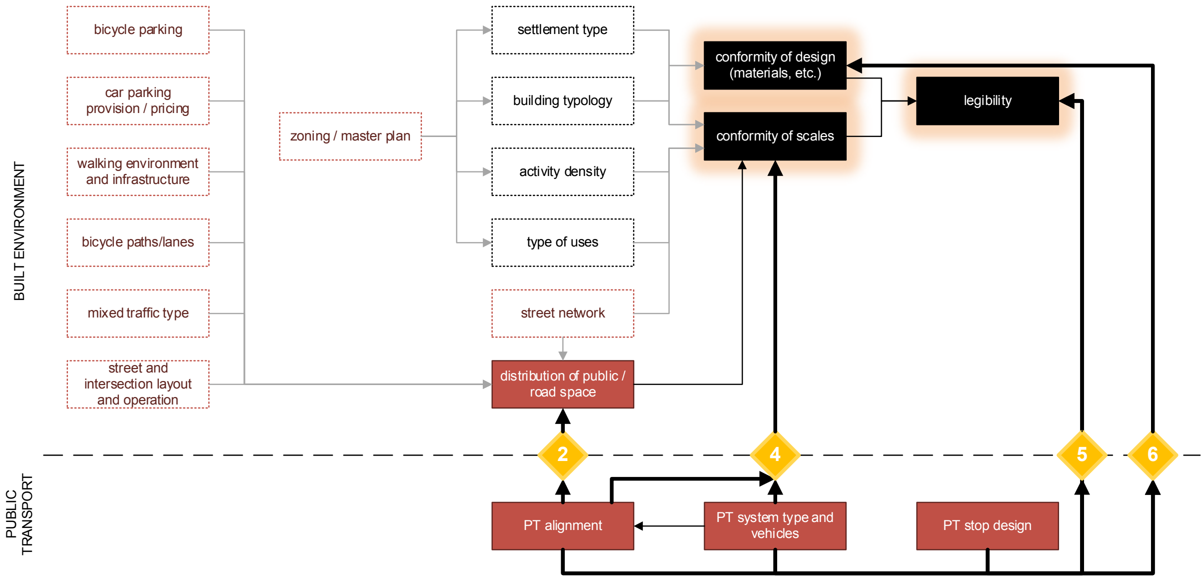

Figure 7: System elements diagram for effect chain analysis on conformity of scales, legibility, and conformity of design

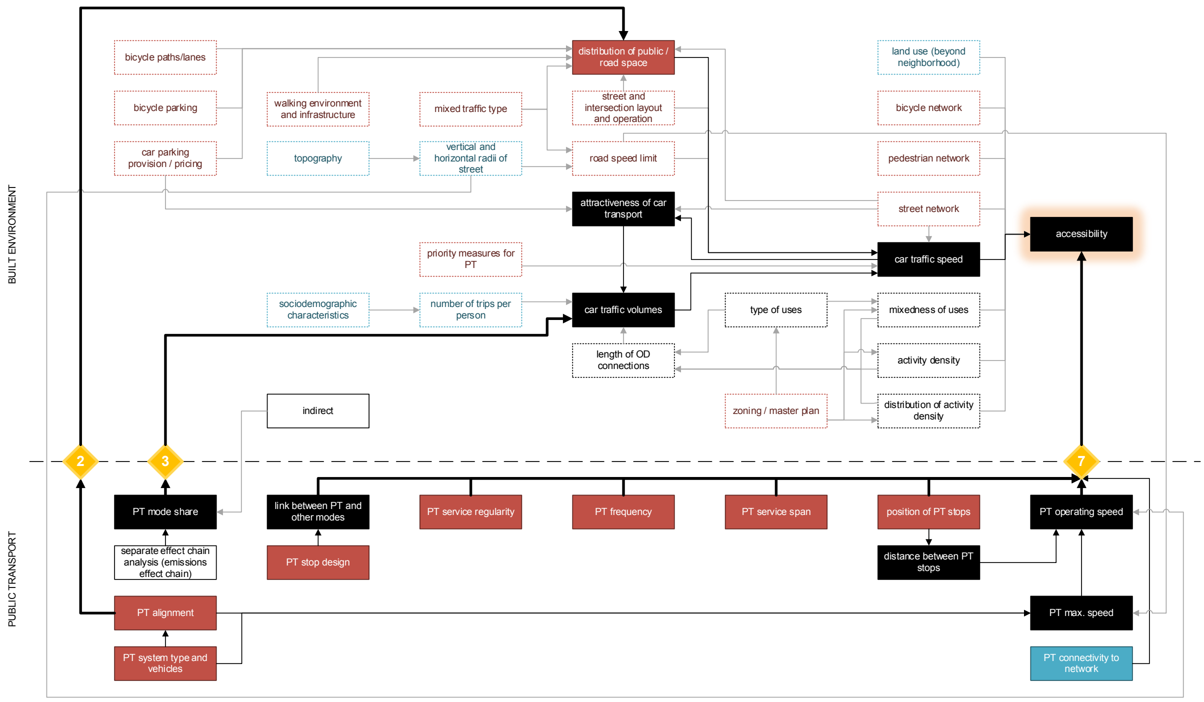

Figure 8: System elements diagram excerpt for effect chain analysis on accessibility

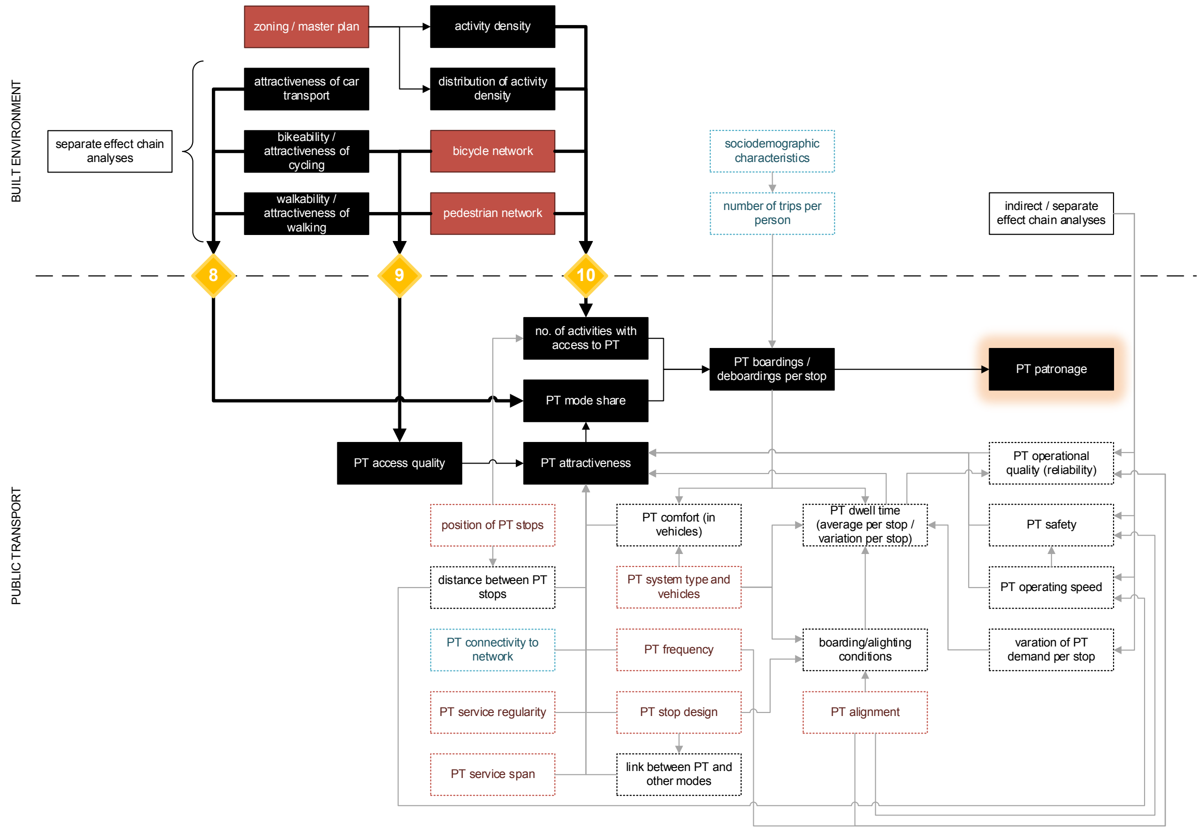

Figure 9: System elements diagram excerpt for effect chain analysis on PT patronage

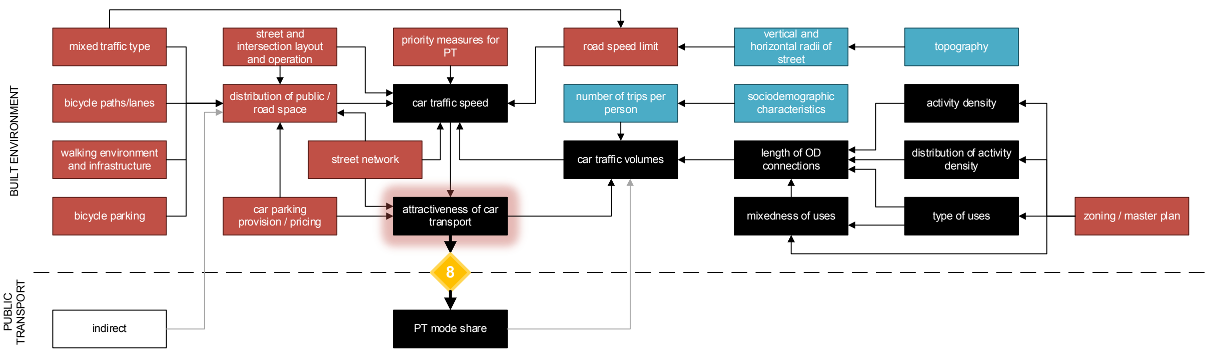

Figure 10: System elements diagram subexcerpt for effect chain analysis on PT patronage – influences on attractiveness of car transport

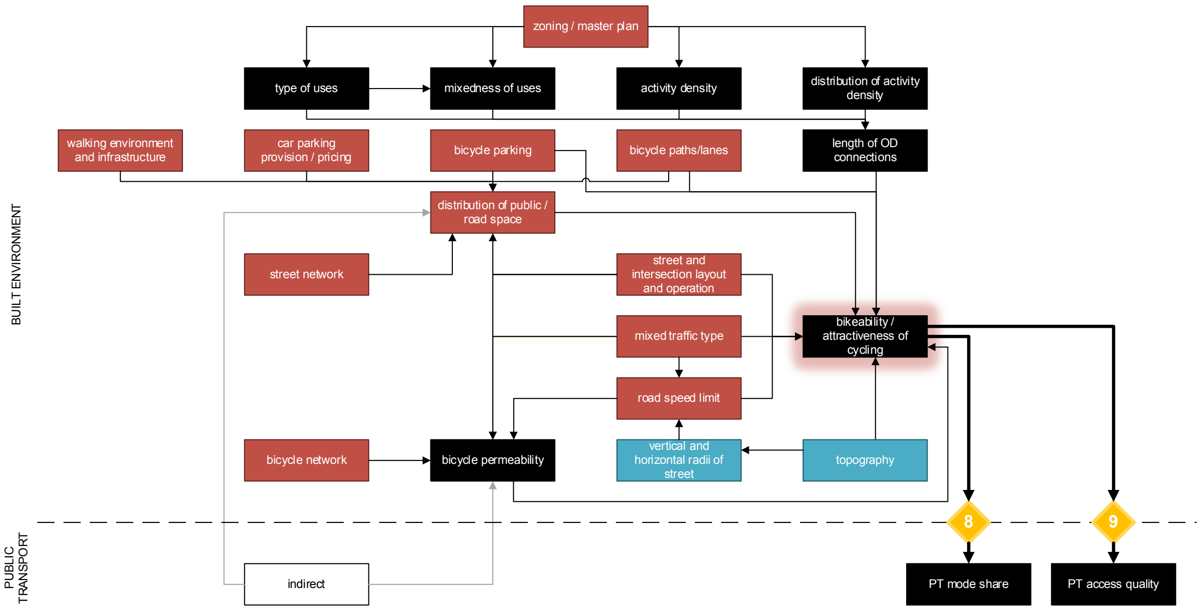

Figure 11: System elements diagram subexcerpt for effect chain analysis on PT patronage – influences on bikeability

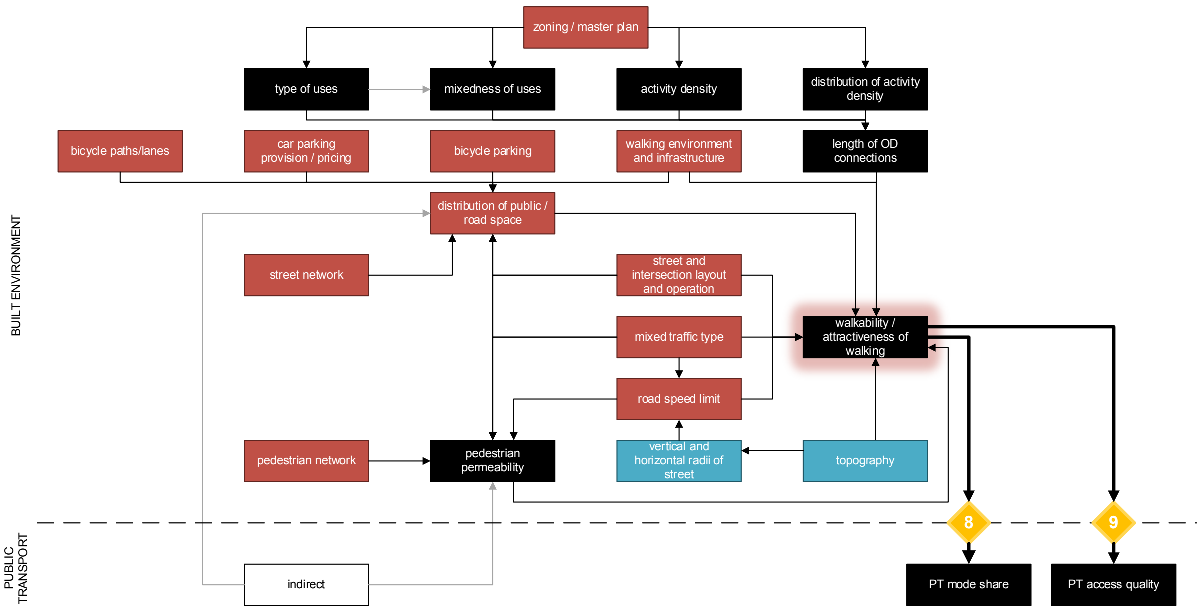

Figure 12: System elements diagram subexcerpt for effect chain analysis on PT patronage – influences on walkability

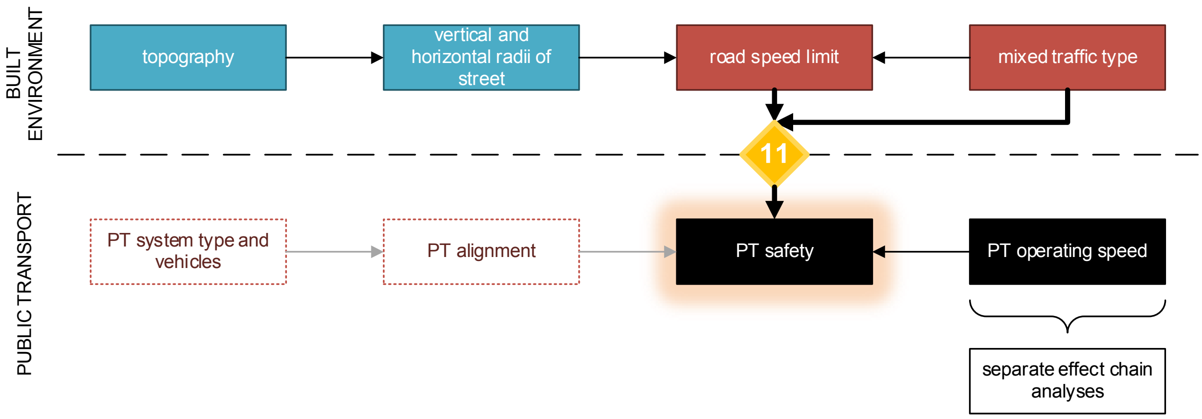

Figure 13: System elements diagram excerpt for effect chain analysis on PT safety

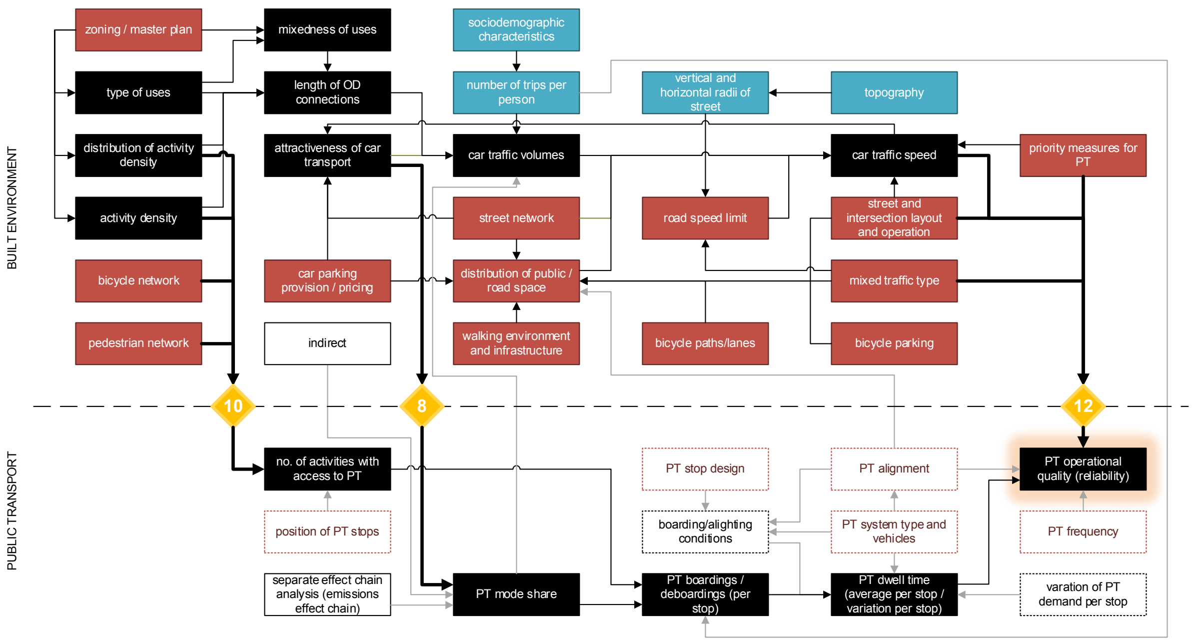

Figure 14: System elements diagram excerpt for effect chain analysis on PT operational quality (reliability)

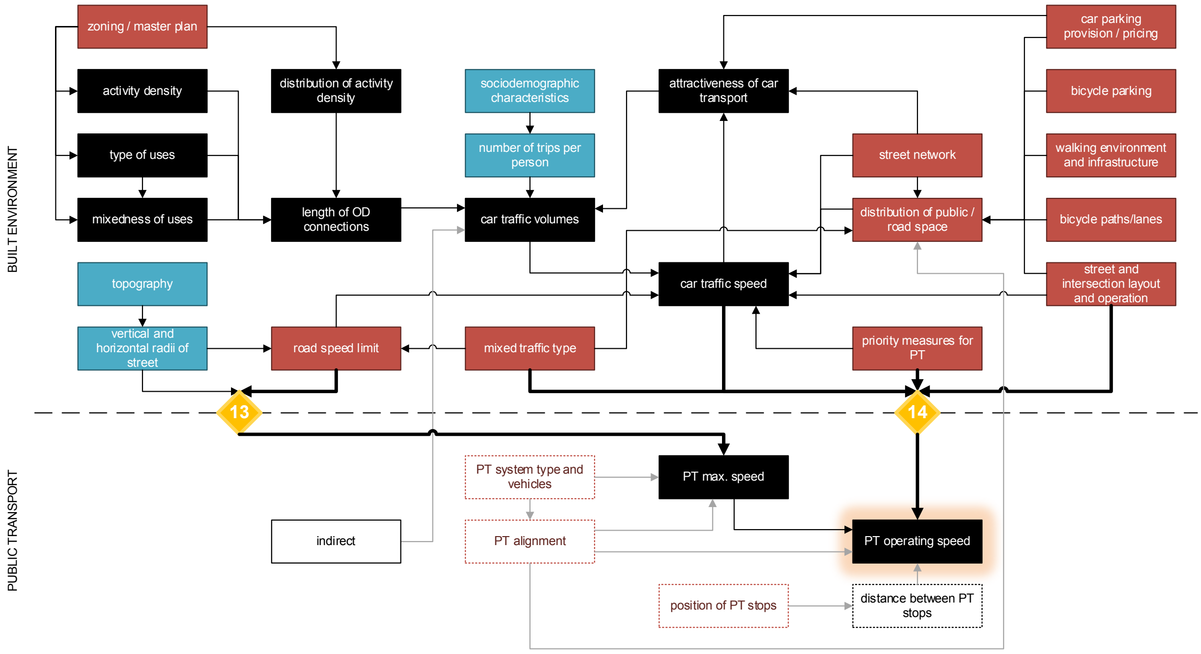

Figure 15: System elements diagram excerpt for effect chain analysis on PT operating speed

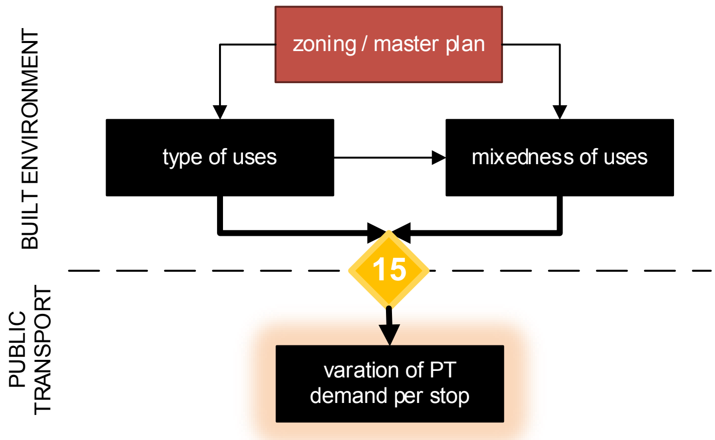

Figure 16: System elements diagram excerpt for effect chain analysis on variation of PT demand

8 Appendix II: Elements of the system elements diagram, influences between them, and respective sources

Table 3 summarizes the constitutive elements of PT and BE that are included in the system elements diagram (left column) and the influences between them (middle column). Furthermore, it lists literature sources for these influences (right column). The order of the elements follows the structure domain (BE appears before PT) – element type (from result to input element) – thematic sector (from city / region and network to location / building and stop). Note that since the system elements diagram depicts interactions qualitatively, the relevant question is only whether an interaction between two elements exists, and not how strong it is.

Table 3: Elements in the system elements diagram, interactions between them, and literature sources; interactions between diagram domains are set in bold

System map element	Influenced by	Literature sources for influence
BE | result element | neighborhood		
BE attractiveness	emissions	(Banister 1997, van Poll 1997, Marti 2012)
	mixedness of uses	(Burns 2005, Day et al. 2006, Marti 2012, Angélil et al. 2013)
	diversity	(Burns 2005, Ewing and Handy 2009, Angélil et al. 2013, Cilliers and Timmermans 2016)
	bikeability	(Southworth 2003)
	walkability	(Southworth 2003, Schmidt 2004, Burns 2005, Southworth 2005, Lahart et al. 2013)
	legibility	(Burns 2005, Kenworthy 2006, Koltsova, Kunze, and Schmitt 2012, Marti 2012)
	conformity of scales	(Southworth 2003, Ewing and Handy 2009)
	conformity of design	(Schmidt 2004, Day et al. 2006, Cilliers and Timmermans 2016)
	accessibility	(Cervero 2001, Southworth 2003, Axhausen 2008, Curtis 2008, Koltsova, Kunze, and Schmitt 2012, Angélil et al. 2013)
BE | variable element | city		
car traffic volumes	attractiveness of car transport	(Weis and Axhausen 2009)
	length of OD connections	(Banister 1997, Ewing and Cervero 2010)
	number of trips per person	direct influence
	PT mode share	direct influence
attractiveness of car transport	car traffic speed	(Buehler 2011)

	car parking provision and pricing	(Buehler 2011, Waraich and Axhausen 2012)
	street network	(Axhausen 2008)
BE | variable element | neighborhood		
emissions	car traffic volumes	(Banister 1997, Marti 2012)
car traffic speed	car traffic volumes	(Siebel and Mauser 2006, Helbing 2009)
	street network	(Ortigosa and Menendez 2014)
	road speed limit	direct influence
	priority measures for PT	(Guler and Menendez 2014)
	distribution of public and road space	(Ortigosa and Menendez 2014)
	street and intersection layout and operation	(Ortigosa and Menendez 2014, Guler and Menendez 2014)
mixedness of uses	zoning / master plan	direct influence: zoning / master plan defines possible uses
	type of uses	direct influence: type of uses defines their mixedness
diversity	mixedness of uses	(Ewing and Cervero 2010)
	sociodemographic characteristics	(Ewing and Handy 2009)
settlement type	zoning / master plan	direct influence: zoning / master plan defines which kind of settlement is possible
bikeability	length of OD connections	(Day et al. 2006, Menghini et al. 2010, Coffel et al. 2012, Winters et al. 2013, Olaru and Curtis 2015)
	bicycle permeability	(Dill 2004, Coffel et al. 2012, Weidmann, Kirsch, et al. 2013, Winters et al. 2013)
	bicycle paths / lanes	(Menghini et al. 2010, Coffel et al. 2012, Weidmann, Kirsch, et al. 2013, Winters et al. 2013, NACTO 2014)
	mixed traffic type	(Day et al. 2006, Lahart et al. 2013, Weidmann, Kirsch, et al. 2013, Winters et al. 2013)
	road speed limit	(Day et al. 2006, Lahart et al. 2013, Weidmann, Kirsch, et al. 2013)
	distribution of public and road space	(Weidmann, Kirsch, et al. 2013, NACTO 2014)
	street and intersection layout and operation	(Weidmann, Kirsch, et al. 2013, NACTO 2014)
	bicycle parking	(Coffel et al. 2012, Weidmann, Kirsch, et al. 2013)
	topography	(Menghini et al. 2010, Coffel et al. 2012, Weidmann, Kirsch, et al. 2013, Winters et al. 2013)
walkability	length of OD connections	(Day et al. 2006, Grob and Michel 2011, Coffel et al. 2012, Olaru and Curtis 2015)
	pedestrian permeability	(Schmidt 2004, Southworth 2005, Day et al. 2006, Ewing and Cervero 2010, Grob and Michel 2011, Coffel et al. 2012, Lahart et al. 2013)
	walking environment and infrastructure	(Jacobs 1993, Southworth 2005, Grob and Michel 2011, Coffel et al. 2012, Lahart et al. 2013, NACTO 2013, Olaru and Curtis 2015)

	mixed traffic type	(Day et al. 2006, Grob and Michel 2011, Coffel et al. 2012)
	road speed limit	(Day et al. 2006, Ewing and Handy 2009, Lahart et al. 2013)
	distribution of public and road space	(Schmidt 2004, Grob and Michel 2011, Lahart et al. 2013, NACTO 2013)
	street and intersection layout and operation	(Grob and Michel 2011, Lahart et al. 2013, NACTO 2013)
	topography	(Day et al. 2006, Grob and Michel 2011, Coffel et al. 2012, Kittelson & Associates et al. 2013, Weidmann, Kirsch, et al. 2013)
activity density	zoning / master plan	direct influence: zoning / master plan defines possible densities
distribution of activity density	zoning / master plan	
length of OD connections	mixedness of uses	(Banister 1997)
	activity density	(Banister 1997)
	distribution of activity density	(Banister 1997)
	type of uses	(Banister 1997)
BE | variable element | public space / road section		
legibility	conformity of scales	(Marti 2012)
	conformity of design	(Burns 2005, Marti 2012)
	PT system type and vehicles	(Olesen and Lassen 2016)
	PT alignment	(Burns 2005, Olesen and Lassen 2016)
	PT stop design	(Olesen and Lassen 2016)
conformity of scales	settlement type	(Carmona et al. 2010)
	activity density	logical derivation: density, certain use types, and the road network directly affect urban scale
	type of uses	
	street network	
	building typology	(Carmona et al. 2010)
	distribution of public and road space	(Burns 2005, Carmona et al. 2010)
	PT system type and vehicles	(Olesen and Lassen 2016)
	PT alignment	(Olesen and Lassen 2016)
conformity of design	settlement type	(Kenworthy 2006)
	building typology	(Kenworthy 2006)
	PT system type and vehicles	(Olesen and Lassen 2016)
	PT alignment	(Schmidt 2004, Burns 2005, Besier 2013, Olesen and Lassen 2016)
	PT stop design	(Schmidt 2004, Olesen and Lassen 2016)
bicycle permeability	bicycle network	(ASTRA 2008)
	mixed traffic type	(ASTRA 2008)
	road speed limit	(ASTRA 2008)
	street and intersection layout and operation	(ASTRA 2008)
	PT operating speed	derived from pedestrian permeability – separation effect of PT also affects cyclists
	PT frequency	

	PT alignment	
pedestrian permeability	pedestrian network	(ASTRA 2015)
	mixed traffic type	(ASTRA 2015)
	road speed limit	(ASTRA 2015)
	street and intersection layout and operation	(ASTRA 2015)
	PT operating speed	(Schmidt 2004); similar effects as roads (Kelly et al. 2011)
	PT frequency	(Schmidt 2004); similar effects as roads (Kelly et al. 2011)
	PT alignment	(Korve et al. 1996); similar effects as roads (Kelly et al. 2011)
BE | variable element | location / building		
accessibility	mixedness of uses	(Banister 1997, Handy and Niemeier 1997, Cervero 2001, Day et al. 2006, Curtis and Scheurer 2010)
	car traffic speed	(Handy and Niemeier 1997, Axhausen 2008, Curtis and Scheurer 2010, Olaru and Curtis 2015)
	activity density	(Banister 1997, Cervero 2001, Day et al. 2006, Curtis and Scheurer 2010)
	distribution of activity density	(Banister 1997, Curtis and Scheurer 2010)
	street network	(Axhausen 2008, Curtis and Scheurer 2010)
	bicycle network	(Cervero 2001, Curtis and Scheurer 2010, Olaru and Curtis 2015)
	pedestrian network	(Cervero 2001, Curtis and Scheurer 2010, Day et al. 2006, Olaru and Curtis 2015)
	land use (beyond neighborhood)	(Handy and Niemeier 1997, Axhausen 2008, Curtis and Scheurer 2010)
	PT operating speed	(Axhausen 2008, Curtis and Scheurer 2010, Olaru and Curtis 2015)
	link between PT and other modes	(Curtis and Scheurer 2010, Coffel et al. 2012)
	PT service span	(Kittelson & Associates et al. 2013)
	PT frequency	(Curtis and Scheurer 2010, Olaru and Curtis 2015)
	PT service regularity	(Kittelson & Associates et al. 2013)
	position of PT stops	(Murray et al. 1998, Murray and Wu 2003)
	PT connectivity to network	(Curtis and Scheurer 2010)
type of uses	zoning / master plan	direct influence: zoning / master plan defines possible uses
building typology	zoning / master plan	direct influence: zoning / master plan defines possible building types
BE | point of influence | neighborhood		
car parking provision and pricing	–	
street network	–	
pedestrian network	–	
bicycle network	–	

zoning / master plan	–	
BE | point of influence | public space / road section		
bicycle paths / lanes	–	
walking environment and infrastructure	–	
mixed traffic type	–	
road speed limit	mixed traffic type	(Forbes et al. 2012)
	vertical and horizontal radii of street	(Forbes et al. 2012)
priority measures for PT	–	
distribution of public and road space	car parking provision and pricing	direct influences: the shares of the constitutive elements of public space determine its distribution
	street network	
	bicycle paths / lanes	
	walking environment and infrastructure	
	mixed traffic type	
	street and intersection layout and operation	
	bicycle parking	
	PT alignment	
street and intersection layout and operation	–	
BE | point of influence | location / building		
bicycle parking	–	
BE | input element | city		
land use (beyond neighborhood)	–	
BE | input element | neighborhood		
number of trips per person	sociodemographic characteristics	(Handy and Niemeier 1997, Scheiner and Holz-Rau 2007, Rickwood, Glazebrook, and Searle 2008, Weis and Axhausen 2009)
sociodemographic characteristics	–	
topography	–	
BE | input element | public space / road section		
vertical and horizontal radii of street	topography	direct influence

PT | result element | network		
PT productivity	PT patronage	(Kittelson & Associates et al. 2013)
	PT operating speed	(Orth, Weidmann, and Dorbritz 2012, Nägeli et al. 2013)
	PT operational quality (reliability)	(Van Oort and van Nes 2008, Carrasco, Fink, and Weidmann 2012)
	PT safety	(COST TU1103 2015)
	variation of PT demand per stop	(Weidmann 1994)

PT | variable element | network		
PT mode share	PT attractiveness	(Vrtic et al. 2000, Scheiner and Holz-Rau 2007, Arrington and Cervero 2008, Rickwood, Glazebrook, and Searle 2008, Curtis and Scheurer 2010, Kittelson & Associates et al. 2013)
	attractiveness of car transport	(Vrtic et al. 2000, Curtis and Scheurer 2010)
	bikeability	logical derivation: attractiveness of other modes determine the comparative attractiveness and thus mode share of PT and of mixed-mode systems (PT + walking / cycling)
	walkability	
PT attractiveness	PT comfort (in vehicles)	(Kittelson & Associates et al. 2013)
	PT operating speed	(Rickwood, Glazebrook, and Searle 2008, Curtis and Scheurer 2010, Currie, Ahern, and Delbosc 2011, Kittelson & Associates et al. 2013, Nägeli et al. 2013)
	PT operational quality (reliability)	(Babalik-Sutcliffe 2002, Van Oort and van Nes 2008, Carrasco, Fink, and Weidmann 2012, Kittelson & Associates et al. 2013, Weidmann, Orth, et al. 2013, Bernal, Welch, and Sriraj 2016)
	PT safety	(Kittelson & Associates et al. 2013, COST TU1103 2015)
	distance between PT stops	(Murray and Wu 2003, Kittelson & Associates et al. 2013)
	PT access quality	(Coffel et al. 2012, Kittelson & Associates et al. 2013)
	PT dwell time (average / variation per stop)	(Murray and Wu 2003, Currie, Delbosc, and Reynolds 2012, Weidmann, Orth, et al. 2013)
	link between PT and other modes	(Coffel et al. 2012)
	PT service span	(Kittelson & Associates et al. 2013)
	PT frequency	(Babalik-Sutcliffe 2002, Rickwood, Glazebrook, and Searle 2008, Currie, Ahern, and Delbosc 2011, Kittelson & Associates et al. 2013, Weidmann, Orth, et al. 2013)
	PT service regularity	(Kittelson & Associates et al. 2013)
	PT stop design	(Coffel et al. 2012)
	PT connectivity to network	(Babalik-Sutcliffe 2002)
PT | variable element | line		
PT patronage	PT boardings / deboardings (per stop)	direct influence
PT comfort (in vehicles)	PT boardings / deboardings (per stop)	(Orth, Weidmann, and Dorbritz 2012, Kittelson & Associates et al. 2013)
	PT system type and vehicles	(Kittelson & Associates et al. 2013)
PT | variable element | section		
PT operating speed	PT max. speed	(Nägeli et al. 2013)
	distance between PT stops	(Nägeli et al. 2013, Fadaei and Cats 2016)
	PT alignment	(Nägeli et al. 2013, Fadaei and Cats 2016)
	car traffic speed	(Nägeli et al. 2013)
	mixed traffic type	(Nägeli et al. 2013)

	priority measures for PT	(Nägeli et al. 2013, Fadaei and Cats 2016)
	street and intersection layout and operation	(Nägeli et al. 2013, Fadaei and Cats 2016)
PT operational quality (reliability)	PT dwell time (average / variation per stop)	(Weidmann 1994, Kittelson & Associates et al. 2013, Carrasco 2015)
	PT frequency	(Carrasco 2015)
	PT alignment	(Carrasco 2015, Fadaei and Cats 2016)
	car traffic speed	(Kittelson & Associates et al. 2013, Nägeli et al. 2013)
	mixed traffic type	(Carrasco 2015)
	priority measures for PT	(Kittelson & Associates et al. 2013, Carrasco 2015, Fadaei and Cats 2016)
	street and intersection layout and operation	(Kittelson & Associates et al. 2013, Carrasco 2015, Fadaei and Cats 2016)
PT safety	PT operating speed	(COST TU1103 2015, Marti et al. 2016)
	PT alignment	(Korve et al. 1996, Currie and Reynolds 2011, COST TU1103 2015, Marti et al. 2016)
	mixed traffic type	(Korve et al. 1996, COST TU1103 2015, Marti et al. 2016)
	road speed limit	(Cheung et al. 2008, COST TU1103 2015)
PT max. speed	PT system type and vehicles	(Nägeli et al. 2013)
	PT alignment	(VBZ 2008, BVB 2013)
	road speed limit	(Nägeli et al. 2013, COST TU1103 2015)
	vertical and horizontal radii of street	(VBZ 2008, BVB 2013)
distance between PT stops	position of PT stops	direct influence
PT | variable element | stop		
varation of PT demand per stop	**mixedness of uses**	(Suzuki, Cervero, and Iuchi 2013, Orth and Weidmann 2014, Orth, Frei, and Weidmann 2015)
	type of uses	(Orth and Weidmann 2014, Orth, Frei, and Weidmann 2015)
PT boardings / deboardings (per stop)	PT mode share	direct influence
	no. of activities with access to PT	(Babalik-Sutcliffe 2002, Ewing and Cervero 2010, Guerra and Cervero 2011, Gutiérrez, Cardozo, and García-Palomares 2011)
	number of trips per person	direct influence
PT dwell time (average / variation per stop)	varation of PT demand per stop	(Weidmann 1994, Nägeli et al. 2013)
	PT boardings / deboardings (per stop)	(Weidmann 1994, Currie, Delbosc, and Reynolds 2012, Nägeli et al. 2013)
	boarding / alighting conditions	(Weidmann 1994, Currie, Delbosc, and Reynolds 2012, Fadaei and Cats 2016)
	PT system type and vehicles	(Weidmann 1994, Fadaei and Cats 2016)
link between PT and other modes	PT stop design	(Coffel et al. 2012)
no. of activities with access to PT	position of PT stop	(Coffel et al. 2012) and logical derivation: relative location of activities and PT stop
	activity density	

	distribution of activity density	together with pedestrian and bicycle networks determine no. of activities within a certain network distance from PT
	bicycle network	
	pedestrian network	
PT access quality	**bikeability**	(Murray et al. 1998, Schlossberg and Brown 2004, Ewing and Cervero 2010, Coffel et al. 2012, Jiang, Zegras, and Mehndiratta 2012, Kittelson & Associates et al. 2013, Park, Choi, and Lee 2015) and logical derivation: given that access to PT is based on walking and cycling, the respective networks and quality aspects define quality of PT access
	walkability	
	bicycle network	
	pedestrian network	
boarding / alighting conditions	PT system type and vehicles	(Weidmann 1994)
	PT alignment	(Currie, Delbosc, and Reynolds 2012)
	PT stop design	(Weidmann 1994, Currie, Delbosc, and Reynolds 2012)
PT | point of influence | line		
PT system type and vehicles	–	
PT service span	–	
PT frequency	–	
PT service regularity	–	
PT | point of influence | section		
PT alignment	PT system type and vehicles	(Weidmann et al. 2011)
PT | point of influence | stop		
PT stop design	–	
position of PT stops	–	
PT | input element | network		
PT connectivity to network	–	

9 Appendix III: Measuring points overview

Table 4 lists all measuring points identified in the system elements diagram excerpts (see Appendix I), and the effect chain analyses they appear in.

Table 4: Measuring points overview

No.	Description	Appears in effect chain analysis on
1A	Influence of PT on pedestrian permeability of the BE	walkability
1B	Influence of PT on bicycle permeability of the BE	bikeability
2	Influence of PT on distribution of public and road space	walkability
		bikeability
		emissions
		conformity of scales
		legibility
		accessibility
3	Influence of PT on car traffic volumes	emissions
		accessibility
4	Influence of PT on conformity of scales of the BE	conformity of scales
5	Influence of PT on legibility of the BE	legibility
6	Influence of PT on conformity of design of the BE	conformity of design
7	Influence of PT on accessibility	accessibility
8	Influence of BE on PT mode share	PT patronage
		PT reliability
9	Influence of BE on PT access quality	PT patronage
10	Influence of BE on number of activities with access to PT	PT patronage
		PT reliability
11	Influence of BE on PT safety	PT safety
12	Influence of BE on PT reliability	PT reliability
13	Influence of BE on PT max. speed	PT operating speed
14	Influence of BE on PT operating speed	PT operating speed
15	Influence of BE on variation of PT demand per stop	variation of PT demand per stop