International Transport Forum

Synergies from Improved Cycling-Transit Integration: Towards an integrated urban mobility system

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Towards an integrated urban mobility system

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Abstract

Improved integration of cycling and transit has the potential to overcome the fundamental limitations of each mode by combining their opposite strengths of flexibility and action radius. The benefits of such integration potentially extend beyond user benefits and the trip level. We present seven conceptual mechanisms that lead to *synergies*, understood as benefits not attributable to cycling or transit in isolation, but to their integration only. As an illustration, we analyse and allocate such synergies by a case study of the Dutch cycling-transit system. Where the practical absence of cycling has limited such potential in many locations elsewhere, the recent resurgence in cycling practice and culture, especially in urban agglomerations, enables new opportunities for improved cycling-transit integration. Urban agglomerations are also the locations where land-use and mobility related issues seem particularly pressing and where we claim cycling-transit synergies are strongest. The article concludes with a discussion of implication and application.

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Introduction

Worldwide we observe an increasing interest to live, work and spend time in cities. Urban areas expand, densify and transform rapidly. This trend is generally considered favourable for fostering strong and sustainable economies (e.g. Glaeser, 2011; Shlomo, 2012; Fuller and Romer, 2016; PBL, 2016; Raspe et al., 2015). This also puts the question of urban mobility at the forefront as never before. The question is not just how to accommodate rapidly increasing travel within, to and from cities using existing concepts and practices. The urban revival is a new phenomenon and not compatible with 60 years of car-based mobility perspectives (e.g. Duany et al, 2000; Sheller and Urry, 2000; Urry, 2007), so it is also a question about *which* new mobility concepts and practices are to be used. In and around cities, space is heavily contested and additional disturbances or environmental impacts are unwanted. Instead, increasing popular demand calls for attractive, lively, clean and dynamic urban landscapes. Physical and economic realities place severe restrictions to changes of urban mobility systems. In recognition of such constraints, we are hard-pressed to actually deliver urban accessibility effectively, efficiently and urgently.

There are opportunities too. Increasing densities and transformative developments together with growing economic and political power of cities and city-regions provide opportunities to align urban mobility needs with new mobility concepts. The net influx of people and functions into cities has continued despite rising housing costs and constraints on car mobility (both through congestion and policy). This at least implicitly indicates that car accessibility seems of reduced priority for cities as constraints have not slowed the influx.

This paper investigates a transport system that is scalable to cater for urban mobility needs while sustainable and compatible with attractive streets and public space. It is the combination of two opposite yet synergistic transport modes: a) rapid mass transit for efficient, concentrated travel flows on the long hauls and b) walking and cycling for flexible movement of diffuse flows on short distances. Both modes are scalable, sustainable and don't impair high quality public space. Yet, these modes on their own only serve highly distinct and partial travel segments. Integration of both modes should aim to tightly connect the strengths of each mode (speed and efficiency on long distance for transit vs. speed and flexibility on short distance for cycling) with the opposite weaknesses of the other mode (intrinsic low door-to-door accessibility of transit vs. limited action radius of cycling). An area with good cycling-transit integration then is one where cycling acts as a natural part of the transit system, offering a solution to the limited door-to-door connectivity problem of transit, or equally, where the transit system acts as a natural extension of the cycling system, offering a solution to the action radius problem of cycling. A rationale of cycling-transit integration exists when the costs required for either sub-system and their integration with the benefits derived from both systems now delivering full accessibility while compatible with high quality public space. This paper targets the scope, the mechanisms and allocation of such synergies.

Previous work on combinations of cycling and transit is relatively thin but is growing (Krizek and Stonebraker, 2010). Research has mostly focused on the relative importance of the bicycle for trains (e.g. Rietveld, 2000; Keijer and Rietveld, 2000; Martens, 2004; Brons et al., 2009; Pucher and Buehler 2009; Givoni and Rietveld, 2007; Heinen et al., 2010), on the effects this combined use has on replacing car-trips and for sustainable transport (e.g. Martens, 2007; Tight et al., 2011), or on modelling their combined performance (e.g. Van Nes et al., 2014; La Paix and Geurs, 2015; Brands et al., 2014;

Debrezion et al., 2009). This article continues from the integrated perspective as presented by Krizek and Stonebraker (2010) and Kager et al. (2016a), focusing on the underlying, distinct components and mechanisms that explain why and how cycling-transit integration functions.

The second section explores the components of such a hybrid transportation system in practice. The third section discusses by which theoretical mechanisms synergistic benefits are created. The fourth section assesses to what degree these components, mechanisms and benefits have materialised in the Netherlands by means of a case study. The fifth section integrates the applied theory and results from the case study and discusses the allocation of benefits from improved cycling-transit integration. The final section concludes and frames cycling-transit integration in light of the pressing quest for sustainable, effective and efficient urban transport.

Components of cycling-transit integration

This section reviews the practical components that determine the degree of cycling-transit integration, referring to Krizek and Stonebraker (2010) and Kager et al. (2016a) for a theoretical underpinning. Here, the focus is on the *functions* of these components for cycling-transit integration. Aspects like the how-to, the how many, form, process or organisation are considered outside the scope of this article, and covered in for example deliverables of the 'BikeTrainBike' project (2016) and by the Rail Delivery Group (2016).

Cycling and transit infrastructure and culture

Fundamental to cycling-transit integration – and the consequent achievement of synergies – is the local provision of infrastructure and culture to actually use either sub-mode (e.g. Martens 2004, Cervero et al. 2012). Changing an existing transport culture or the provision of such infrastructure (such as bike lanes, bike route signage, junction facilities, rail corridors, bus lanes, stations) from a situation with only limited demand is an issue for many jurisdictions. Complexity derives from how usage levels are intertwined in both directions with infrastructure provision and a favourable culture whereas – most specifically so for cycling – research stresses how no single solution ('silver bullet') suffices to induce increased mode share or cultural change (Pucher et al., 2010; Pucher and Buehler, 2012; Forsyth and Krizek, 2010; Harms et al., 2016). The function of infrastructure and culture in cycling-transit integration is that it is a basic prerequisite for achieving benefits from integration. Yet, to an extent, the local absence of infrastructure of the one sub-mode to some degree can be compensated by infrastructure of the other sub-mode if local circumstances or opportunities make this a better choice (e.g. Brons et al., 2009).

Bicycle rental schemes

Next to the provision of infrastructure, we consider bicycle rental schemes the second most important component of cycling-transit integration. Bicycle rental has the potential to efficiently provide with bicycle availability, particularly for trips that do not start or end at home. By their nature, transit trips generally take a traveller out of the reach of their home location and hence away from their (actual or potential) own bicycle. Therefore this 'away' destination part of transit journeys is crucial to cycling-transit integration (Griffin and Sener, 2016; Fishman, 2016; Ma et al., 2015; Jäppinen et al., 2013; Kaltenbrunner, 2010; Martin and Shaheen, 2014).

Transit journeys typically concentrate their destinations in urban (sub-)centres, where space is at a premium and where environmental impacts are felt by large numbers of people (both by citizens and by visitors). In the typical case where such (sub-)centres are large or where also the bordering fringes of such centres encompass many activity locations (in lower intensity but distributed over a larger area), this leads to diffuse travel patterns over extended distances. The diffusion of travel make transit less an option, the distances make walking less an option. In contrast, the above conditions are favourable for cycling, but only if bicycle availability is organised by a bicycle rental scheme. Alternatives like letting travellers park a 'second bike'[1] at such locations or take their bikes on board are discussed later, but are considered less efficient, less flexible and less scalable in providing bicycle availability away from home.

The above arguments are in line with why 'feeder' transit systems typically are (and need be) better developed at the travellers' destination side of a transit journey compared to the travellers' home-side. It might be tempting to conclude that the focus for cycling should therefore be at the other (home) side of transit journeys. First, such reasoning does not alter the relative functions of the cycling component for the home trip end versus the away from home trip end. A second reason is how feeder transit services and cycling from a destination station serve distinct travel markets: feeder services best serve a limited number of 'thick' demand streams over somewhat prolonged distances; cycling best serves large numbers of 'diffuse' streams. Also some people prefer sitting while travelling, high safety, ride speed or comfort, while other people prefer exercise while travelling, flexibility, individual adaptation or effective speed and reliability. We think either market segment should be accommodated for to arrive at highest synergies where it matters most – urban (sub-)centres – while symbiotically 'feeding' the (mass) rapid transit system and the urban land-use system at the same time. A third reason for a focus on non-home locations is the considerable amount of transit trips which neither start from the home location nor travel towards the home location. Even in case just 20% of transit trips thus lack a home trip end, it means there is 50% more 'away from home' trip ends for transit journeys than 'home' trip ends.[2]

Bicycle parking facilities at transit stations

A third component of cycling-transit integration is bike parking at transit stops or stations. In light of the above discussion, bike parking should mostly be targeted for short-term parking (up to 24 or 48 hours) of privately owned bicycles around the home location of travellers. Catering for longer-term parking is proposed for non-urban locations or for transit stops where a cycling rental scheme is not feasible. In urban (sub-)centres, bike rental schemes deliver higher flexibility, space-efficiency and cost-efficiency ultimately to the benefit of travellers, transit operators and cities, and hence should be considered first, in particular ahead of long-term bicycle parking.

Integrated planning and operation

A fourth component is integrated planning and operation of the transit and cycling systems. In our view, the strongest effects of cycling-transit are synergistic effects, i.e. those that extend beyond the isolated cycling system or the isolated transit system. Only integrated planning and management is able to respond effectively and efficiently to changes, threats and opportunities in the total system and to be able to relate synergistic benefits to planning, investments and operation costs and policy-development. In such light, we propose to indeed frame *cycling as a means of transit* when cycling is used to travel to or from transit stations. Or likewise, we propose to frame rapid *transit as an extension to the cycling system*, and as a crucial component of cycling policy where it intends to make an impact on urban accessibility. Integration would ideally be the responsibility of a common organisation that plans and intervenes for either sub-mode, but if not, at least governments should adopt a common approach for both sub-systems in their planning, tendering, granting concessions and other regulation and thus providing with interfaces for both worlds to connect.

Integrated information and arrangements

The ultimate component of cycling-transit integration, and perhaps final proof thereof, is the seamless integration in signage, maps, travel information, communication, registration, payment, ticketing, subscriptions, leasing or marketing of either transit or cycling. Basic examples are cycling signs showing direction to transit stops, transit network maps showing main cycling routes and cycling facilities or the availability of bike rental locations in travel planners. Other examples are integrated offerings of bike rental or bike lease as part of transit subscriptions, integrated ticketing of bike parking facilities or bike rental with transit tickets, advanced travel planners including cycling options based on (pre-stored or derived) user’s preferences, and dynamic transit/cycling routing information in public spaces.

Bike-on-board facilities and regulation

The possibility to take a bicycle on board of trains (or similarly, on racks in buses) in a reliable, hassle-free, cheap, fast and comfortable way would probably constitute the best integration of cycling and transit from the perspective of individual travellers. Unfortunately, once more than a marginal percentage of travellers follow this approach it is not feasible for the transport system as a whole. Bike-on-board lacks scalability because of the amount and value of the space taken by the bicycle, but also the additional time needed to embark and disembark. The additional space required in stations, on platforms, on stairs or elevators would also quickly become impractical if more than a small number of people took bikes on board. Accommodating mass use of bike-on-board reduces transit’s cost-efficiency, space-efficiency and speed which together constitute its fundamental rationale.

We thus think bike-on-board should be regulated in most contexts as it works against cycling-transit integration or even general transit usage (cf. Krizek and Stonebraker, 2010). Having said this, bike-on-board can have a function in specific contexts, for example:

- kick-starting cycling-transit integration, where this is not current practice,
- to increase transit ridership when and where spare capacity is available, e.g. off-peak,
- to accommodate the movement of bikes on long hauls for single journeys, e.g. for regional travel supporting cycle tourism,
- to temporarily compensate for insufficient provision of other components, such as bike parking.

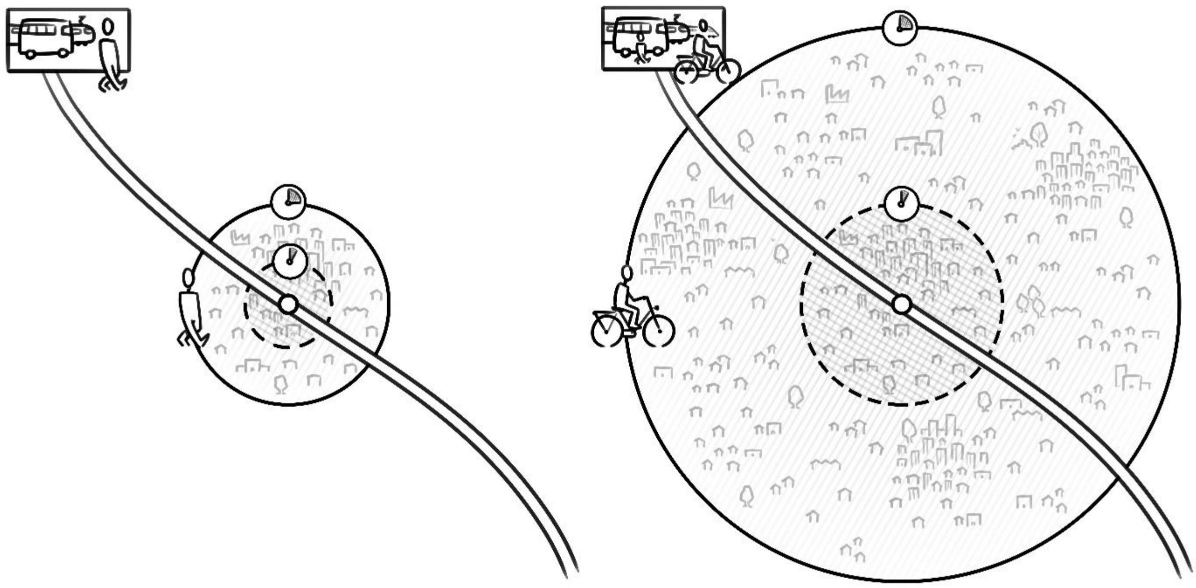
Mechanisms how improved cycling-transit integration affects land-use and mode use

We present seven mechanisms through which higher levels of cycling-transit integration affects land use and travel patterns. This prepares the way for the following sections that discuss how such changes lead to synergies for travellers, transit operators and urban agglomerations. Ultimately all mechanisms derive from the potential of cycling to be highly flexible, requiring limited resources and having competitive speeds for ‘inner-urban’ distances of up to (around) 5 km. Alternative access modes lack at least one of these qualities for such distances: walking lacks speed, cars require high resources, feeder transit lacks flexibility, ultimately restricting general applicability or scalability for these modes.

Increased catchment areas

The mechanism: Access and egress travel is often referred to as transit’s ‘first and last mile problem’ or even as the ‘FMLM-problem’ whereby wide stop spacing creates inconveniently long walking times to access services (e.g. Liu et al. 2012). Cycling potentially offers large catchment area, so such terminology ignores the primary potential of cycling access. For example, with a typical cycling speed 3 times higher than rapid walking (15-18 km/hr vs 5-6 km/hr), cycling can cover 3 times the *distance* in the same time. In particular, the quadratic relationship between radius and area means that cycling can cover a 9 times larger catchment *area* than walking (Givoni et al., 2007; Flemming, 2016).

Figure 1. **Mechanism of increased catchment areas**

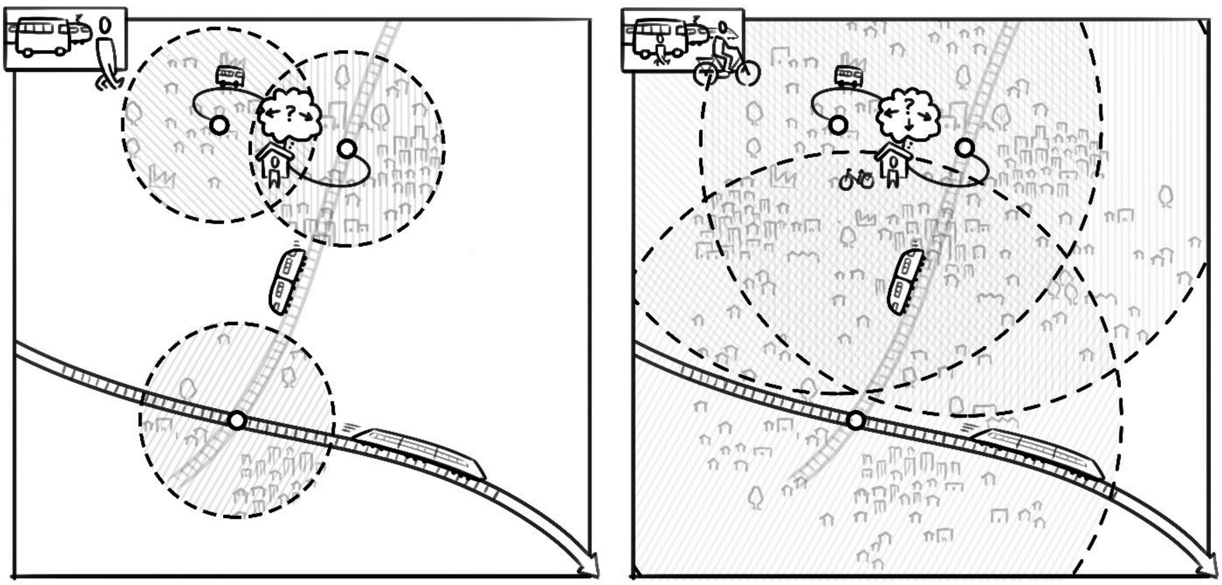


The effects: The increase of catchment areas of existing stations thus connects up to 9 times more people and places to a given station or transit service than walking. At the same time, the flexibility and resources for cycling are comparable to walking, the speed is comparable with car and transit travel (at least for urban contexts and distances up to 3-5 km), while cycling also outperforms the car alternative in scalability (better scalable for high usage) and feeder transit alternatives (better scalable for low usage, for example at specific times of day or specific travel corridors). In such ways, the resulting increase of catchment areas works in two ways; more households are connected to a higher number of stations, increasing the travel options for these households, while also stations are connected to more households, increasing the traveller base of these stations, their services and their facilities.

The mechanism: The nine-fold increase in catchment areas compared to walking not just extends catchment areas but typically also introduces overlaps of the catchment areas of nearby stations, especially in urban settings. These overlaps are of particular interest as transit services are typically based on a hierarchy where faster, more comfortable, more direct and/or more frequent services typically stop only at selected, primary, stops. Also the facilities of such stops can be much better than those of transit stops lower in the transit hierarchy. Inclusion of a cycling option lessens the distance constraint of walking and so opens up the possibility that more distant stations may be used based on preferences on acceptable contexts, frequencies and durations of cycling trips, the attributes of transit stations, or a combination of both. Such choice may also be based on the characteristics of the cycling routes towards such alternative stations, e.g. one cycling route may lead through an attractive area (like a park or a street with a lot of people, sights or activities), the other might allow inclusion of intermediate destinations (a shop, a restaurant, visiting someone), a third might have uninterrupted cycling infrastructure, etc.

In some cases, access or egress stops that are far from the actual origin or destination may offer better journey attributes than the closest stop. This is particularly relevant for stops served by high-speed transit. For example, acceptable walking time to transit stops varies significantly in the Netherlands, from say 500 m for a local bus-stop versus 2.2 km for an Intercity (IC) station (Keijer and Rietveld, 2000; Wang and Liu, 2013, p.117). Likewise we expect cycling catchment areas to vary from a typically acceptable 1.5 km to a local station to a typically acceptable 7 km towards an IC station (cf: Krizek and Stonebaker, 2010). With such distances, geographic topology is a further consideration. Cycling 6 km to an IC station 'in the right direction' (towards the final destination) can be preferred over cycling 4.5 km 'in the wrong direction' to another IC station all else being equal. This is because even if both stations are served on the same line, even a fast IC train takes a comparable time to cover 10.5 km compared to cycling the additional 1.5 km.

Figure 2. **Mechanism of increased choice**

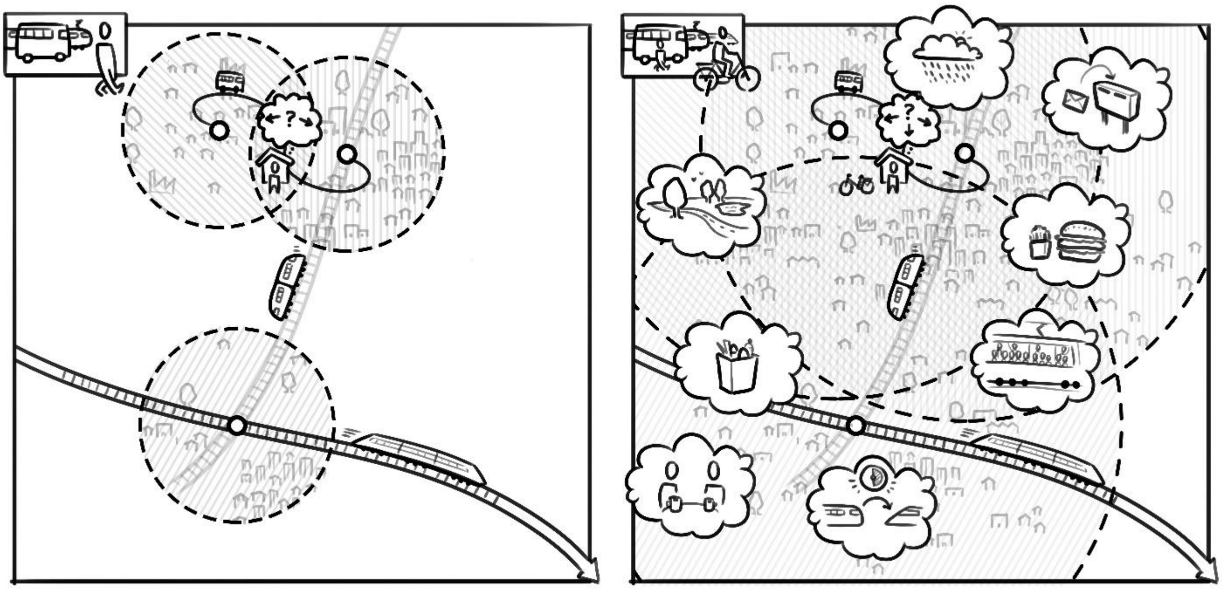


The effects: Because alternative transit stops and services cluster in and around urban centres, if not at walking distance then at cycling distance, the nine-fold increase in catchment area dramatically increases station choice. This allows better matches by offering a better portfolio of options to travellers: in varying travel contexts; under varying traveller preferences; or through increased resilience to planned or unplanned disturbances. Finally, we consider that to cycle as an access mode is an optional choice in itself because there is virtually always the option of (extended) walking or the option of lower-hierarchy feeder modes, leading to option value even when cycling is not selected. Integrating cycling with transit thus greatly increases (individual) choice on how to use the transit system and hence its adaptability to varying travel contexts and individual preferences.

Increased customisation of transit journeys

The mechanism: A powerful derived effect of increased choice is the increased ability to personalise transit journeys. Thinking about cycling-transit integration, it is easily understood that access and egress journeys by bicycle allows for fully individual travel behaviour for the cycling part of the journey, similar to walking or car access. However, the above mechanism of increased station choice also allows for effective customisation of the 'transit' part of the journey: which station is selected, which transit services are used, when to depart, how much transfer time to allow, which transfer facilities to use or how to respond to planned or unplanned disruptions in the transit system.

Figure 3. **Mechanism of increased customisation**

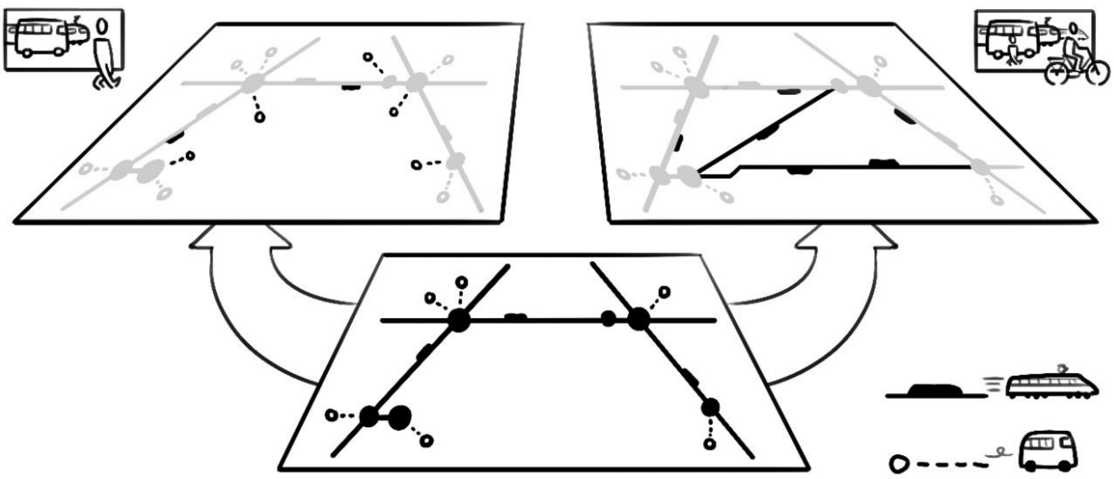


The effects: Increased customisation of transit allows travellers to better uphold their structural and incidental preferences. For operators and governments, synergies arise from a more targeted use of services and facilities where and when they offer heterogeneity in their services. Such heterogeneity can be the offering of station services or on-board services, differences in rolling stock or pricing arrangements, but also the crowding or reliability level of a service. In such situations, high use of cycling can lead to improved, self-organising distribution of travellers and better use of spare capacity, provided information on such aspects is shared or known to travellers by experience. This may increase satisfaction, willingness to pay, use frequency or utilisation of transit services.

Increased market base for (widely spaced) rapid transit systems

The mechanism: A second mechanism invoked by the larger catchment areas and higher choice is that cyclists typically prefer rapid services and their stations (Krizek and Stonebaker, 2010). Rapid transit stops are not and cannot be offered at low mesh-sizes[3] so on average they are accessed from further away than transit stops lower in the hierarchy. Therefore cycling as an access mode typically gives the opportunity to bypass a nearby stop or station with a slower transit service, and instead cycle further to a stop or station that offers rapid services. In this way, the traveller makes an investment in using a bicycle, perhaps spending more time on access travel, and perhaps spending time or money to park or borrow the bicycle.

Figure 4. **Mechanism of increased market base for rapid transit systems**



However, on the mass transit component of the journey the traveller may save on fares, save on travel time and avoid one or more transit transfers. Also the traveller perhaps circumvents the unavailability of the feeder service at the moment it is needed or its unreliability that could spoil the connection at the transfer station. Through this mechanism, improved cycling-transit integration leads to increased relative market share for rapid transit and/or transit travel at prolonged distances. Second, where alternative stations serve alternative rapid services, cycling is capable of sorting out travellers to and from the right rapid service. Finally, cycling can function to complement rapid transit availability at an isolated stop or in areas where no feeder transit exists and hence increase the effectiveness of rapid transit lines.

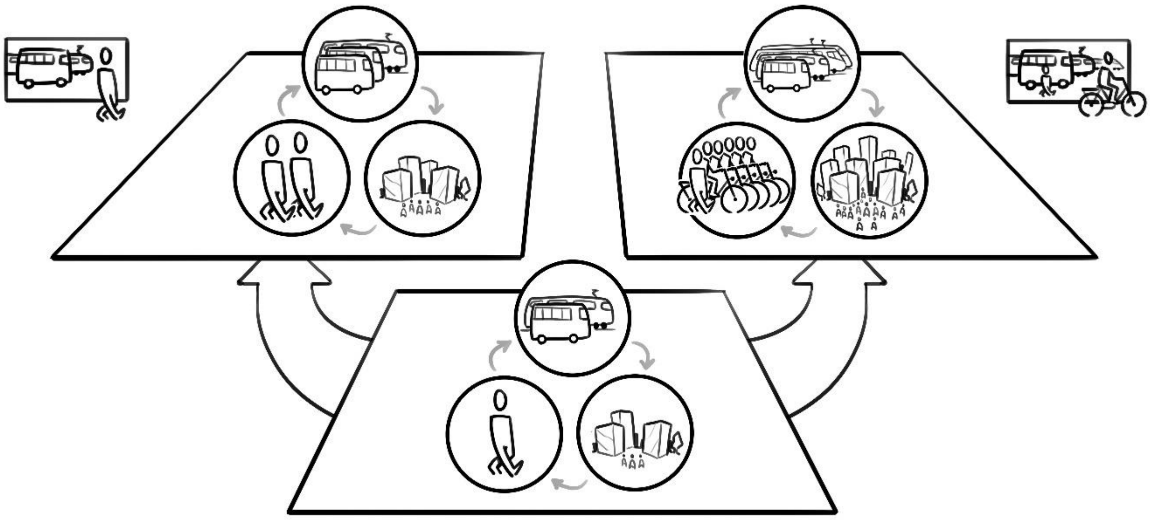
The effects: Increased demand for rapid transit systems can improve their business case, so they can be offered in higher frequency, at a lower mesh-size or in higher variety. When and where this happens (the extensive Dutch national IC-rail system is an example of this, as discussed in the next section), this benefits all transit travellers, not just those who combine transit with cycling. Faster transit typically leads to higher transit efficiency per person-km travelled because of better utilisation of stations, rolling stock and personnel, higher willingness to pay and/or higher ridership.

Increased competitiveness of transit, cycling and cities

The mechanism: All the above mechanisms ultimately lead to higher competitiveness of transit, maintained over extended areas, be it for travellers who access it by bicycle or for the ones who choose not to do so. This in turn might invoke secondary effects in higher ridership and in land-use effects by means of a feedback loop. Where the rapid transit system and the urban system become more attractive, we expect people will also be willing to make more effort to get to and from a station, including from somewhat extended catchment areas and/or by changes in their travel behaviour (all else being equal). For this, we make an analogy with people travelling to airports even though airports are typically not in the vicinity, nor how it is typically easy or cheap to park in comparison to other locations. However, where airports offer increasingly attractive connections to increasingly popular (foreign) locations, people are also increasingly willing to 'invest' in getting to and from airports. Where such effects are occurring at the lower scale of rapid transit services and the increasingly popular (urban) destinations they connect to, the bicycle is a means to connect extended catchment areas between 1 and (at least)

5 km around rapid transit stops, in turn feeding the rapid services, their stations and connected destinations and thus closing the feedback loop (cf. Wegener, 1999; Duffhues and Bertolini, 2016).

Figure 5. **Mechanism of increased competitiveness of transit, cycling and cities**



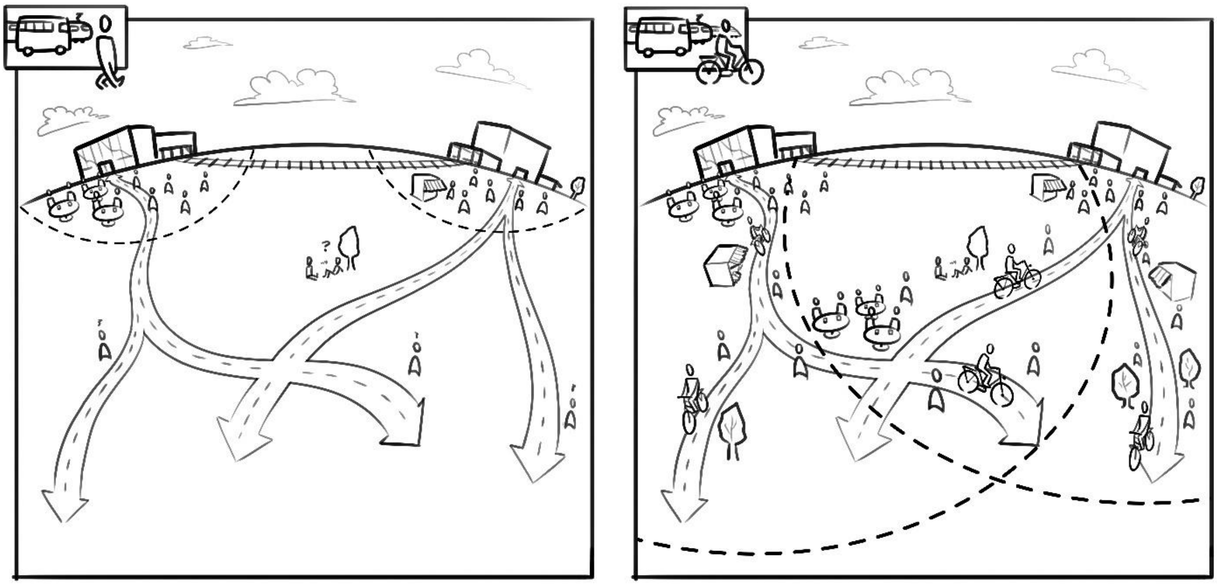
The effects: First of all, higher transit competitiveness maintained over extended areas increases the likelihood of individuals using it for a higher share of their travel needs, or in being less likely to shift away from it. By nature of the transit system, locations with access to rapid transit services are highly selective and localised (namely the surrounding areas of (rapid) transit stops or areas within the effective catchment area of such stops). These locations are typically in cities. Better connectivity and accessibility make cities stronger via increased location choices for home, work, business, education or leisure, creating a feedback loop between cities and higher use of walking, cycling and transit. Apart from this geographic leverage factor, also on a personal level we expect that once a threshold is reached in the share of trips made by walking, cycling and transit combined, this may start to impact long-term decisions like trip destination choices, car ownership or sharing arrangements, transit or parking subscriptions, location choice and activity patterns, any of which offers synergistic feedback to the transit system, the cycling system and the urban system. Such behavioural responses were for example documented by Klinger (2017) who measured how people newly moving into a city that is transit or cycling-friendly are likely to adopt multi-modal mobility practices, even if coming from origin cities lacking such mobility options, and where this effect outweighs the opposite effect of people newly moving in the other direction.

Increased liveliness of public space

The mechanism: Where cycling-transit integration is mature, the above mechanisms all lead to a net increase in the number of people out in public space on their ways to or from transit stations. This is the case if people make more frequent use of transit, for an increased variety in departure/arrival times and in varying travel contexts, leading to more access and egress journeys by foot or by cycling and for larger parts of the day.

The effects: A growing body of literature highlights how an increased number of 'faces in the street' improves perceptions of urban space as safer and more attractive. The number of people to look at, make eye contact with, and the feeling of being exposed to other people, all increase a feeling of belonging and being connected to a place and its people. This feeling of connectedness contributes to well-being and happiness, visiting frequency, attractiveness of locations, health, expenditure, amount of time spent at locations, land-value, social capital, the fostering of self-expression and ultimately ‘producing culture and identity’ (Middleton, 2016; Aldred, 2010; Brömmelstroet et al, 2017; Leyden, 2003; Jensen, 2010). The number of faces on the street also seems a decisive factor in attracting even more people, be it for a walk during lunch, as a meeting location, to drink a coffee, to visit as a tourist, or in locating yourself or your company, and hence in creating ‘lively, safe sustainable and healthy cities’ (Appleyard et al, 1981; Gehl, 2010).

Figure 6. **Mechanism of increased liveliness of public space**

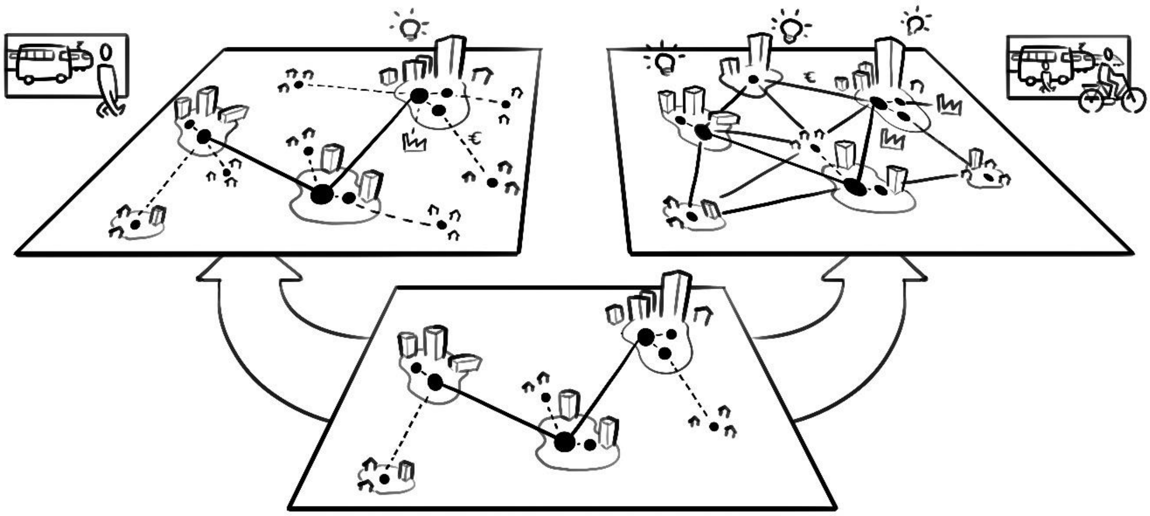


Land use change that supports agglomeration effects

The mechanism: Accessibility by transit and/or by cycling is highly distinct from accessibility by car. For car travel, distance is the key factor determining accessibility. The provision of fast highways on corridors where many people travel somewhat stretches distance people wish to travel on such corridors, but this is countered by (the risk of) congestion and slower urban traffic once off the highway. Such counter-effects often render accessibility by car relatively geographically neutral in practice. In contrast, accessibility by transit and cycling options are highly geographically selective. For transit, the availability, speed, frequency and comfort are all highly dependent on the urbanisation level of both the origin and destination of a trip. An example is how transit services in low density suburbs and rural areas are almost universally low quality. For cycling, the appeal is very sensitive to distance and much less by urban density. However, because the base location for cycling is either the home location, or an external location where cycling availability can be organised (like bicycle rental, a second bicycle at a train station or bike-on-board), in practice this again translates that cycling is on average geographically restricted to where most people live and where (rapid) transit services are available, i.e. again predominantly in and around cities (cf. Buehler and Pucher, 2012). Thus, when combined, cycling-transit accessibility is primarily influenced by the urbanisation level at trip origins and destinations, not primarily by distance. This is the opposite for car accessibility.

By delivering such accessibility, cycling and transit reinforce densities in the (extended) vicinity of stop locations of rapid transit. And since rapid transit stops are usually found in cities (where densities are usually strong already), cycling-transit integration tends to reinforce poly-nuclear structures of separated densities rather than dispersed concentrations of people and functions. Such structures are characterised by having both 'centrality of distant connections' favouring even more transit (Amin and Thrift, 2002) and increased 'average proximity' (or 'immotility') favouring even more use of active modes (Banister, 2005; Tight et al., 2011; Ewing and Cervero, 2011; Ferreira et al., 2017). Exactly such spatial patterns have been identified a key success factor for agglomeration economies (Dijkstra et al., 2012; Duranton and Puga, 2004; Combes and Gobillon, 2014) and 'information(al) economies' (Castells, 2009). In summary, where car-based accessibility leads to sprawl without densities being created (Duany et al., 2000; Urry, 2007, p.120; Merriman 2009), cycling-transit integration fosters opposite land-use patterns, namely poly-nuclear (sub-)centres at intermediate distances.

Figure 7. **Mechanism of land use change that supports agglomeration effects**



The effects: By strengthening poly-nuclear agglomerations rather than dispersion, greater cycling-transit integration allows sub-centres to grow larger, in higher density or in higher number. This leads to increased opportunities for people and services to find a location offering the right accessibility level at the right cost, and favours urban economies. Stronger poly-nuclear agglomerations also facilitate trip-chaining by combining activities around sub-centres and transfer locations, thus creating a similar feedback loop as discussed earlier for individual cities, but here for poly-nuclear network cities.

Case study: cycling-transit integration in the Netherlands

We now analyse the integration of cycling and transit in the Netherlands. Both modes are heavily used: 28% of all national trips are made by bicycle, covering 10% of all national km travelled and 21% of travel time; transit accounts for 5% of trips, 12% of km travelled and 13% of travel time (National Travel Survey, 2010-2014).[8] For around three million citizens who live in or frequent the (sub-)centres of the main Dutch urban agglomeration ('Randstad', including Amsterdam, Rotterdam, The Hague and

Utrecht), cycling and transit together have surpassed the car-system as the primary transportation system (ibid.).

For the Dutch transit system, the train mode is a quasi-monopolist in delivering rapid transport over longer distances. Table 1 illustrates how the train accounts for just 5.7% of all daily transit services in the Netherlands and 21% of all service km, yet the train covers 97% of express services and 99% of express service km (>60 km/hr effective, straight-line speed).[5] Also, out of all 365 transit stops in the Netherlands offering such express transit, 92% of these stops are railway stations.[6]

Table 1. **Dutch transit segments and shares of train**

Transit segment[4]	**# services**		**# service-km[5]**		**# stop areas[6]**	
	total	%train	total	%train	Total	%train
Local (<30 km/hr)	84 759	0%	884 242	0%	8 186	0%
Hybrid (30-40 km/hr)	20 324	0%	489 323	0%	9 894	5%
Rapid (40-60 km/hr)	6 803	36%	231 593	39%	1 918	24%
Express (>60 km/hr)	4 191	97%	326 512	99%	365	92%
Total	**116 077**	**6%**	**1 931 670**	**21%**	**20 363**	**2%**

Note: Speeds and service-km based on straight lines between subsequent stops.5
Source: www.OpenOv.nl7

The above theory suggested how cycling and transit deliver disproportionally higher benefits when cycling is combined with rapid transit services. Nationally, bicycles are used for 47% of access travel and 13% of egress travel to train stations; usage is significantly lower in conjunction with local buses and trams (KiM, 2016). When averaging access and egress travel, cycling outweighs both walking and transit feeder services for travel to and from train stations. For the above reasons, we choose to focus on cycling-*train* integration as representing the typical case of cycling-*transit* integration for the Netherlands.

Components

Here, we describe and grade how the Netherlands performs against the components of cycling-transit integration specified above using a qualitative scoring of **(+)**, **(0)**, **(-)**. For brevity, in the description we combine a selection of aspects like actual usage and component maturity level, current policy priorities as well as trends and expectations on each of these.

- Cycling and transit infrastructure and culture:

  - Infrastructure and culture for cycling is at a high level in the Netherlands, especially for inner-urban cycling (Harms et al, 2015). Cycling has the highest modal share for all Dutch trips up to 7.5 km (national average: 34%, inner-urban average: 45%) and is typically the fastest travel mode up to 3 km, which is the average length of a cycling trip. The country has strong institutions, engineering culture and regulation favouring cycling. More than 60% of the Dutch population has a positive attitude towards cycling (Harms et al, 2016) **(+)**.

  - For rail transit, the Netherlands features an extensive and dense rail network, with two trains per hour being the norm on nearly all railway lines from early morning till midnight. Between the most important towns, there are on average four rapid intercity rail services per hour and at least two additional local services, having average market shares of up to 70% for travel between their centres.[8] Since 2000, major investments have been made in the capacity, attractiveness and the facilities of main rail stations, as well in travel information and ticketing **(+)**.

  - Investments in cycling and transit infrastructure and culture have not typically been expected to make a contribution to cycling-transit synergies. Apart from this connection not included in business cases for investment or operation, also planning culture, measurement, demand modelling and management of infrastructure in the Netherlands for either sub-mode do not explicitly include actual or potential benefits from increased cycling-transit integration **(0)**.

- Bicycle rental schemes:

  - Many cities in the world have recently developed extensive and successful public short-term bicycle rental schemes (Fishman, 2016). Public bike rental in the Netherlands is instead almost exclusively related to train stations and geared towards domestic train travellers for day and multi-day hire. This 'OV-fiets' system has consistently grown by 20% to 100% on a year-to-year basis since its small-scale introduction in 2004, with 800 bikes and 0.1 million annual rentals, by 2016 the nation-wide system had grown to 9 500 bicycles, 300 hire locations and 2.4 million annual rentals. For September 2017, the system has been announced to grow to 16 000 bicycles, with over 3.0 million rentals anticipated for 2017. Such continued growth has gradually and consistently been facilitated and supported by both governments and Dutch Railways up to the current level and is visibly portrayed and expected to contribute to increased train travel **(+)**.[10]

  - Demand for OV-fiets bikes exceeds supply on most days, despite year on year extensions, making the scheme unreliable especially for large stations with high rental rates. Even from a high starting point, access travel has grown strongly between 2003 and 2016, from 33% to 47% of all travellers (Kager et al. 2016a). At the same time hardly any increase in cycling usage for egress travel was recorded, with OV-fiets mostly serving egress travel (percentages varied between 11% and 13%, ibid.). This stable pattern in combination with the difference in order of magnitude indicate a significant market potential on the non-home side of train journeys where bike-rental schemes – despite 10 years of rapid growth – still don't seem to tap into. Furthermore, the introduction of the OV-fiets was initially a private initiative which – although receiving a limited subsidy in its pilot phase – never had been planned for by active policy intervention. In particular, the enduring success (20% to 100% annual growth rates), was barely envisioned, understood or investigated and until today is hardly integrated in business cases or policy development **(-)**.

  - Pricing of the bike is inflexible – 24-hour blocks without flat-rate subscriptions or discount options – and the nominal price has risen by 40% since its introduction (from a flat-fare EUR 2.75 in 2003 to EUR 3.85 in 2017). This, in conjunction with the above mentioned continued growth and the marked difference between access and egress travel in cycling share are further indication of high latent demand for the cycling scheme and hence underutilisation of its potential in increasing cycling-transit integration (Kager, 2016b) **(0)**.

- Bicycle parking facilities at transit stations:

  - Bicycle parking at rail stations is easily the most visible aspect of cycling-transit integration in the Netherlands. Around 500 000 bicycle parking places were distributed over the 410 Dutch train stations as at 2015, when the population was 17 million and 1.3 million train travellers were recorded per day **(+)**.

- Increasing both quantity and quality of bike parking at train stations has been an active programme since the 1990s and paid for jointly by national and local governments. The current phase between 2013-2020 totals EUR 221 million for around 100 000 additional bike parking spaces.[11] As a flagship project, the coordinated scheme includes for example the extension of total parking capacity around Utrecht Central Station, the largest and busiest station in the Netherlands, from 18 000 bikes in 2015 to a total capacity of 33 000 in 2018. Apart from quantity, large scale replacement schemes have raised and standardised bike parking quality during the last two decades and are still on-going. Increasing attention is also made for seamless transfers by fully integrating bike parking areas to through cycle infrastructure, providing pedestrian bike parking exits right into the station hall and investing in automated ticketing (where applicable), bicycle detection and wayfinding inside the parking area. Finally, there generally is a choice between paid guarded and unpaid unguarded parking areas at stations and separate bike parking areas are available at most entry points of stations. **(+)**.

- With rising costs due to increasingly complex station surroundings and rapidly rising cycling numbers, planning, financing and operation of the facilities is increasingly problematic. Furthermore, it remains undecided who should pay for these facilities. Policy seems insufficient to smooth such continued discussions for subsequent investment phases, for on-going costs, for projects that did not make it into the scheme, or for ex-ante or ex-post assessment of benefits against investment costs. Simultaneously, over 80% of the capacity of many facilities is filled by so-called 'second-bikes' used by travellers for egress transport.[1] Where these travellers only make up 12% of transit journeys, due to their extended parking duration, their bicycles require higher parking capacity compared to the current 47% of travellers *accessing* a station by bicycle. This indicates an imbalance in the expectation of the parking facilities offered and their actual main use **(0)**.

- Integrated planning and operation:

  - Transit and cycling are highly separated when it comes to government, organisation, lobbying, data, research, planning, monitoring and debate. Cycling and transit infrastructure is typically built or adapted where land-use is changing, where safety issues exist or to increase speed, comfort or directness of routes. For example, new bike parking facilities at stations have been proposed where existing facilities were insufficient or cycling rental schemes have been extended where demand exceeded supply. This has led to a problem-based planning frame, not to a more opportunity-based assessment like how it conceptually exists in Transit Oriented Development (TOD) for walking-transit synergies. This practice can be both explained by the fact that cycling-transit synergies are typically not made explicit, anticipated, analysed, measured or evaluated and – implicitly – by the prevailing absence of regulations, tradition, tools, concepts and methodologies to do so **(-)**.

  - Planning for new stations, changes to timetables, major new cycling routes and other elements of transit and cycling policy are for the moment still uncoordinated, although the rigid separation seems to be diminishing and the near future might see breakthroughs here. For example, the subject of cycling-train integration was put high on the recent agenda as part of the Dutch 'Bicycle Agenda 2017-2020' by all Dutch governments layers and partner organisations (Tour de Force, 2017) and the issue similarly receiving higher interest from transit-based initiatives **(0)**.

- Integrated information and arrangements:

- The Netherlands shows only limited development on information integration. Cycling-inclusive travel planners from door-to-door are either lacking or are under-developed. Also pricing arrangements to combine cycling and trains are virtually non-existent **(0)**.

- Recently barriers seem to loosen though, in part related to how both the national 'OV-fiets' public rental bike scheme and many bike parking facilities are subdivisions of Dutch Railways (NS). Examples are a recent marketing campaign by NS that promoted the flexibility of the 'OV-fiets' in conjunction with train travel, accompanied by a combined offer and the Dutch rail planner now stating the current number of available rental bikes at the destination station in all travel queries. In particular the offering of various 'business cards' that (amongst others) cover travel costs by train, feeder transit, rental bike and bike parking subscription in an automated and integrated fashion are examples of successful integration **(+)**.

- In contrast, for students, tourists, or frequent travellers, no targeted cycling-inclusive arrangements exist. For example, most students in the Netherlands enjoy free ridership on both trains and feeder transit services whereas they enjoy no such privileges for cycling related facilities **(-)**.

- Bike-on-board:

  - Bike-on-board is both limited and restricted in Dutch trains. It is forbidden during peak hours, requiring a flat EUR 6 fee when it is allowed, and only a handful of places are available per train. Statistics of bike-on-board are non-existent, but comparing effective bike-on-board capacity to train travel intensity, a maximum of around 1% or 2% of all train journeys can involve a bike on board. Folding bikes can be taken on board everywhere free of charge (including peak hours), but anecdotally are spotted only occasionally and estimated at another 1% or 2%. Despite or because of this limited capacity and apparent (self-)regulation, complaints about this regime are rather unknown. This is considered a merit, especially when taking into account the high number of daily bike-train users who would perhaps prefer to just take their bike on board yet who seem to agree – at least implicitly – that taking a bike on board for general usage is not an option **(+)**.

  - Given the above regulation, the limited bike-on-board options do serve their purpose for limited bike-tourism and for moving a bike or taking a bike where bike rental is not available. In addition, most Dutch high-speed trains are being prepared to allow a limited number of 4 bicycles per train like regular trains. Bike-on-board facilities as well as its regulation thus seem in balance and deliver their (niche) functions **(+)**.

Effects and trends

We next illustrate effects for travellers, transit operators and agglomerations from the observed levels of cycling-transit integration in the Netherlands. We do this by taking a closer look at how various segments of the transit system connect to where people live at walking distance versus cycling distance. We subdivide the transit system based on average speed of transit services, as in Table 1.

- *Increased catchment areas*: Cycling substantially extends the catchment area of transit services in the Netherlands, but in particular for services of higher operating speed. Table 2 illustrates for the Netherlands how walking and cycling connects the Dutch population to transit stops and services. Where 79% of Dutch population is within walking distance (1.25 km or less) of a transit stop serviced by at least 20 daily services[6], this percentage increases to 98% for a cycleable distance (5 km or less).[5] Thus, the cycling-transit option connects an additional 19% of the Dutch population to transit services. The relative importance of cycleable distances is more pronounced when we look at catchment areas for *rapid* transit services. For example for the 365 stopping locations in the Netherlands with fastest transit (see Table 2), only a small minority (10%) of the Dutch population lives at a walking distance from these stops, yet 46% can cycle (or walk) to the same 365 locations. Cycleable options thus connect roughly five times more Dutch citizens to express transit services compared to walking (46% vs 10% of the Dutch population).

Table 2. **Access to transit services, by transit segment and (maximum) distance to stop**

Transit segments[4]	**< 1.25 km (walk)[5]**			**< 2.5 km (bike short)**			**< 5 km (bike long)**		
	cove-rage	# ser-vices[9]	# stop areas[6]	cove-rage	# ser-vices	# stop areas	cove-rage	# ser-vices	# stop areas
Local or faster (any speed)	79%	429	7.9	93%	756	21	98%	1 233	47
Hybrid or faster (>30 km/hr)	51%	186	4.5	79%	282	9.1	93%	435	18
Rapid or faster (>40 km/hr)	19%	165	2.8	44%	213	3.9	63%	286	5.8
Express (>60 km/hr)	10%	133	2.1	28%	159	2.5	46%	202	3.3

Note: Distances and speeds measured in a straight line5. Coverage as percentage of Dutch population (17 million) having access. #services and #stop areas specifying unique transit services9 and stops6 within the catchment area for those who have access. Source: http://www.openov.nl/

- *Increased choice*: Cycling not only connects more people to express transit services, but also connects those people who are connected to more daily express services compared to walking. Table 2 shows how many daily transit services can be accessed from how many transit stops within the given distance and for the given transit segment (the figure represents the average for people who are connected by at least 20 daily transit services). Cycling enables 46% of the Dutch population to access express transit, but it also allows this 46% to choose from 202 such daily transit services[9] on average, which is 52% higher than the 133 services accessible by the 10% in the walking catchment area. Finally, the cycling-accessible rapid services are spread over a higher number of transit stops on average (3.3 stations vs. 2.1 stations for those who have access). This challenges the hub-and-spoke philosophy that is sometimes assumed or pursued in transit system analysis or design: the Dutch transit system offers many examples where access to *multiple* hub stations is needed in order to have access to any available rapid or express transit services in the near vicinity.

- *Increased customisation of transit journeys*: The second section noted that alternative cycling-accessible stop locations can be spread in a circle with a radius of 5 km and that different stations might offer different facilities and services. Also the route towards these stations might differ in many aspects, as might topology and wind direction in respect to the final destination. By having a comprehensive cycling network, choice of alternative stations is increased, but also choice is increased for the related facilities and services, for intermediate routes taken, for opportunities for intermediate stops, for combining activities or for alternative configurations of the integrated transit journey (e.g. in remaining transit distance, required number of changes, frequency of services or amount of backup options).

- *Increased demand for rapid transit systems:* Public transport use in the Netherlands grew strongly between 2005 and 2015, including 22% train passenger-km growth (KiM 2016). The share of cycling as an access mode also grew strongly within this growing market, from around 30% in 2000 to 47% in 2015 (Kager et al. 2016a). Increases in travel volumes and bike access shares have not been evenly distributed over the network. Nor have investments: six major sections of railways have been duplicated from two to four tracks and a high-speed line introduced, and these were all on the direct routes between the five largest Dutch cities. Also all of the central stations of these cities have been renovated and expanded. The new capacity is mostly used to add new express (IC) services and to make ICs run faster. This pattern is repeated in strong growth of cycle volumes to and from IC stations, but stable cycling volumes at surrounding stations. Also in other recent Dutch transit projects; like the increasing of frequencies for regional train lines, the introduction of bus rapid transit ('R-net') and urban light-rail ('Randstad Rail') or the extension of local bus lines, the relative growth of faster and/or more frequent transit was accompanied by an above-average growth of cyclists to and from these services and their stations. These trends confirm that cycling-transit integration leads to the concentration of an increasing portion of travel movements (at least in relative shares) to a smaller number of rapid services and their stations and thus helped the success of the underlying policies that have focused resources on these.

Table 3. **Access to transit services by transit segment and (maximum) distance to stop. Urban areas versus rural areas in the Netherlands**

Transit segments[4]	**< 1.25 km (walk)**[5]			**< 2.5 km (bike short)**			**< 5 km (bike long)**		
	cove-rage	# ser-vices[9]	# stop areas[6]	cove-rage	# ser-vices	# stop areas	cove-rage	# ser-vices	# stop areas
Urban (2.3 m people = 14% of Dutch national population)									
Local or faster (any speed)	99%	1 777	28	100%	3 858	125	100%	6 264	338
Hybrid or faster (>30 km/hr)	61%	546	6.6	94%	1 004	19	100%	1 746	47
Rapid or faster (>40 km/hr)	39%	342	4.4	77%	578	8.3	96%	906	17
Express (>60 km/hr)	25%	227	3.2	64%	348	4.9	89%	522	8.7
Rural (3.6 m people = 21% of Dutch national population)									
Local or faster (any speed)	60%	108	4.4	83%	179	10	95%	347	27
Hybrid or faster (>30 km/hr)	42%	87	3.9	65%	117	7.4	86%	183	15
Rapid or faster (>40 km/hr)	9%	82	2.4	22%	96	3.3	42%	126	4.7
Express (>60 km/hr)	3%	66	1.7	9%	73	1.9	21%	96	2.4

Note: See notes under Table 1, this table offers the same measures but specified for extreme cases of (highly) urban versus rural (three intermediate groups were distinguished but omitted for brevity).
Source: www.OpenOv.nl

- *Increased competitiveness of transit, cycling and cities:* Key for this mechanism is whether or not cycling-transit synergies are condensed into relatively small pockets such that an effective feedback system is created. For the Netherlands and since roughly 2005-2010, there is evidence that such effective feedbacks are being established for (sub-)centres of various cities. For such locations, we observe house prices rising faster than elsewhere, in conjunction with increasing local per-capita cycle use and train use towards, from and in between cities.[14] For these cities, we also observe a rapid net influx of people and functions; for example the Amsterdam population growth in the past decade has largely reversed the population decline from the 1960s until the 1990s (CBS Statline, 2017). This all is typically combined with a gradual but consistent increase of restrictions imposed to the local car system (such as traffic calming, 30 km/h zones, street closures, reductions of parking capacity, increasing parking tariffs, banning of polluting cars). To support the claim that bike-train synergies are condensed into such locations, Table 3 reproduces Table 2 but separately for the most urban and the most rural areas in the Netherlands (boasting 14% and 22% of the Dutch population respectively). From Table 3, we observe that where just 21% of the population in rural areas is connected to express transit services within 5 km, the urban figure is 89%. In addition, this 89% of the urban population on average has more than 5 times the amount of express services to choose from compared to the 21% of rural population where they have access (522 vs. 96 daily express services). Similar patterns can be observed for any other figure in Table 3 in comparison with national averages in Table 2. From these comparisons, we argue that cycling-transit synergies are condensed into urban locations, which is where real estate value, population, economic activity, local bike use and incoming transit flows have all risen rapidly for the last decade, indicating the start of the above described feedback loop (Fleming 2016).

- *Increased liveliness of public space:* The Netherlands features many mid-size cities with intact historical centres and lively, attractive and high-valued public space. Most of these cities also have a major rail station nearby these centres. The high amount of daily train travellers and the high modal shares for walking and cycling in access and egress travel both indicate a significant contribution to local walk and bicycle flows. As an initial estimate, a pilot study on automatic trip detection (discussed in the next section) measured how on average *40% of all registered walk and bicycle kilometres* in (semi-)urban areas are made by people in conjunction with a transit trip.

- *Increased agglomeration effects*: The mechanisms underlying this effect all operate on a long time scale and are complex to analyse in isolation. The Netherlands is renowned for its high cycling levels, but its extensive train system and its poly-centric urban structure are also prominent characteristics of the Dutch land-use/transport system. Since 2005 many of these poly-centric cities share in the trend of urban densification and urban expansion, which corresponded to increasing cycling levels within such cities (Harms, 2014) and train use to and from these cities, which at least anecdotally sustains the argument. This is supported by analysis of Dutch National Travel Surveys showing that both cycling and train use increase disproportionally where cities are located and where these cities are growing.[8]

Cycling-transit trips measured using automatic trip detection

To supplement the above high-level analysis, we complete the case study by looking at detailed transit usage data from a small (and somewhat non-representative) sample. From a pilot study on automated and anonymous trip and mode detection in three Dutch cities[12] we selected all 1 453 transit trips. From this sample, we observed transit trips based on cycling access[13] travel (45% of all train trips) and pedestrian access (21%) or without a known access mode (15%, access or egress trips shorter than 500 m could not be recorded due to detection method but are most likely pedestrian trips), roughly comparable to national averages.

Table 4. **Train trip statistics, by mode of access travel**

Journey statistics[5]	Modes of access and egress travel			Difference
	no access/egress trips recorded*	walk/walk or walk/none	bike/bike, bike/walk or bike/none	
	(both <500 m)	(access and/or egress trip >500m)		
Length of access/egress trip[13] (straight)	-	1.1 ‖ 0.5** km	2.1 ‖ 1.3** km	factor 1.9 ‖ 2.4**
Length of access/egress trip (route length)	-	1.2 ‖ 1.0** km	2.8 ‖ 1.6** km	factor 2.4 ‖ 1.6**
Size of catchment areas	-	1.9 ‖ 0.4** km^2	6.9 ‖ 2.7** km^2	factor 3.6 ‖ 6.6**
Length of transit trip (straight)	21.0 km	26.5 km	32.8 km	+24%
Length of transit trip (route length)	29.0 km	33.4 km	43.0 km	+29%
Length of door-to-door trip (straight)	21.0 km	27.3 km	34.3 km	+26%
Time of access/egress trips (minutes)	-	12 ‖ 2**	10 ‖ 6**	-14% ‖ x3.5**
Time on-board in transit (minutes)	31	29	33	+12%
Time of transfers and wait time (minutes)	9	12	15	+33%
Travel time door-to-door (minutes)	41	54	61	+21%
Walk or ride speed of access/egress trips	-	6.8 km/hr	16.2 km/hr	factor 2.4
Ride speed of on-board transit trip	43.1 km/hr	69.1 km/hr	79.1 km/hr	+15%
Effective door-to-door speed (straight)	30.7 km/hr	30.3 km/hr	33.8 km/hr	+12%
Share in sample (N=1 453 transit trips)	15%	21%	45%	factor 2.1

Note: *Due to detection method, access or egress trips shorter than 500 m in route length have not been recorded. **For transit trips that recorded both an access and an egress trip. Lengths of access and egress trips separated by ‖ are shown by order of distance (longest trip first, regardless of whether it is access or egress from transit station). *Source*: Studio Bereikbaar pilot study on automatic trip detection[12]

One of the most notable differences between the walk-access and cycle-access segments was that the average ride speed of a train when used after being accessed by bicycle averaged 79 km/hr versus 69 km/hr for walk access (Table 4). For this, stations accessed by cycling required an average 2.1 km bike ride in a straight line (2.8 km by road) compared to an average 1.1 km observed for walk trips (1.2 km by road), though excluding trip segments shorter than 500 m inflates the sample average for walking in particular. This makes the average cycling catchment area of stations in this sample $(2.1/1.1)^2$ = 4 times as large. Train journeys involving a cycling segment were 34 km long (in a straight line) versus 27 km for train journeys involving walk access, which accords with our expectations outlined above.

Finally, Table 5 considers only respondents who make two or more transit journeys per week on average (60% of the sample). We further subdivided this group into three equal segments based on the number of cycling trips for access or egress travel detected. The third with highest bike usage on average reported 13.3 weekly transit trips (52% of which involved a cycling segment) that included 430 weekly km by transit.[5] In contrast, the third with lowest bike usage reported on average 7.6 weekly transit trips (16% of which involved a cycling segment), making a total of 258 weekly km by transit.

From this pilot study, we deduce a first estimate that travellers who integrate cycling and transit in above-average frequencies report some 75% more transit trips and 67% more weekly km by transit (compared to travellers reporting under-average use of cycling in conjunction with transit). Most notably, and as a result of this much higher frequency, the ‘frequent cyclists’ in fact made comparable or higher use of both feeder transit and walk trips to and from rail stations as measured in absolute trip frequencies, adding to our claim that cycling and transit operate in synergy rather than in competition, even for feeder transit.

Table 5. **Weekly transit usage of regular transit users, by frequency of access mode**

Statistics for regular transit users (at least 2 transit trips/week during 4 weeks)	33% of users having lowest bike use	33% of users having medium bike use	33% of users having highest bike use
Weekly transit journeys (total)	7.6 trips	10.9 trips	13.3 trips
Weekly transit journeys including bike	1.2 (16%)	5.3 (48%)	6.8 (51%)
Weekly transit journeys including feeder	0.5 (7%)	1.0 (9%)	0.9 (7%)
Weekly transit journeys by walk exclusively	3.9 (51%)	5.3 (49%)	4.3 (32%)
Weekly km by transit[5]	258 km	362 km	430 km

Source: Studio Bereikbaar pilot study on automatic trip detection[12]

Synergies from improved cycling-transit integration

This section describes how increased cycling-transit integration leads to synergies for various beneficiaries. In the discussion we combine theoretical understanding of the mechanisms as described in the third section with observations from the case study in the Netherlands in the previous section. Where this section argues for the presence of benefits from cycling-transit integration, the hurdles to get there are considered out of scope. In particular, the following issues need be addressed when linking specific investments in cycling-transit integration to benefits:

- the variety of distributed components and effects, interacting on different geographical scales, time scales and by means of varying threshold levels (conceptual complexity).
- limited data availability, modelling experience and the relative novelty of interdependent urban growth, increasing transit ridership and emergent cycling (novelty factor).

Traveller benefits

For travellers, combining cycling and transit is argued to provide opportunities to access a higher number of transit services – in particular rapid services – and a larger number of stations to take them from. On average, we expect cycling access to therefore deliver faster and/or more customised transit journeys. For example, the pilot study of Dutch transit users showed that individuals who cycled to stations travelled with train services showing a 15% faster effective ride speed than trains accessed by walking.

Table 1 illustrates how 79% of the Dutch population is connected to (at least) basic transit within a walkable maximum of 1.25 km from home. In the Netherlands, the widespread choice of cycling access is therefore motivated by choice rather than by necessity. Considering that a) 47% of all 1.3 million daily train travellers use their bicycle to access their entry station from such choice, b) a further 13% travels from their destination station onwards by bicycle, where c) these percentages show persistent growth since 2000 (when it was 30% for access and 11% for egress travel), where d) observing significant growth of the total number of train travellers and e) observing high numbers of people parking or renting a bicycle at many stations in spite of insufficient capacity and hence uncertainty, we deduce that individual travellers experience high and growing (net) benefit from this cycling-transit integration. We furthermore note how these benefits are synergistic; choices and their benefits cannot be explained by looking at the cycling trip alone or the transit trip alone. In particular, a stand-alone modal perspective cannot explain station choice (Kager et al., 2016a). Overall, travellers benefit from cycling-train integration by various aspects:

- *Travel time savings:* Travellers have the option of faster travel times (e.g. using faster transit services at a distance, more than offsetting longer access distance) or can make use of network topology by aligning cycling distance with the transit journey.

- *Avoiding transit transfers, feeder transit fares and reducing trip complexity:* Travellers can avoid train-to-train transfers by selecting direct services from alternative stations, or avoiding feeder-to-train transfers by using cycling as the access or egress mode.

- *Personalising journeys:* Travellers can select their own departure time, cycling route, intermediate stops or sub-destinations and (cycling) speed. In addition, and by means of station choice and the related selection of transit services, travellers can also extend their actual control (and feeling of being in control) to aspects of the transit journey.

- *Increased accessibility*: Travellers who choose cycling instead of other access modes can experience a significant net increase in travel options to or from certain locations, including for locations where other transit-based travel options are restricted.

- *Feedback effects*: where feedback loops are established between the urban system, the cycling system and the transit system, in the long run stronger cities and stronger transit systems emerge, offering higher availability and choice in particular for rapid services, benefiting travellers who cycle and who do not cycle alike.

Transit operator benefits

Transit operators aim to transport as many travellers as far as possible, for the least possible input of resources. Transit operators therefore aim to serve ‘thick’ streams of demand: concentrated travel flows of passengers (the transaction base) over a sufficient distance (the fare base) while avoiding cost components such as halting times, indirect routes or speeds below economic base speed. From such a perspective, cycling offers a ‘helping hand’ to transform diffuse travel patterns into higher concentrations of travellers at particular stations, travelling in more concentrated flows to other connecting stations while requiring fewer intermediate stops. This could lead to reduced vehicle cost, personnel cost, infrastructure cost, and at the same time increased reliability, ridership and willingness to pay. Evidence from the pilot study in the Netherlands suggests that choices of cycle-access users of trains are consistent with the objectives of transit operators. Train trips accessed by bicycle operated at a 15% higher average ride speed (79 km/hr vs. 69 km/hr) and cover a 29% longer distance (43 km vs. 33 km) (Table 5).

Although transit and cycling are sometimes framed as competing against each other, in particular feeder transit services, evidence suggests there in fact is a (net) synergistic benefit from increased cycling for both feeder transit and for rapid transit. Where competition between cycling and transit does exist on the trip (segment) level, this competition does not seem to extend to the overall travel behaviour of individuals: transit users making greater use of cycle access in the Netherlands actually perform more transit trips than average (75% more trips by transit, travelling 67% more km as well as an equal usage of feeder services in absolute per capita ridership; Table 5). This outweighs lower (feeder) transit usage on some of the trip segments of these transit trips. Thus, where the *relative* share of feeder trip segments is typically lower, the *absolute* number of per capita feeder trips is typically similar or higher. The synergistic benefits from cycling-transit integration for transit operators are therefore:

- *More concentrated and (self-)organised travel flows* in response to service availability, requiring fewer stop locations, having degrees of flexibility in case of planned or unplanned disruptions.

- *Improving the business case for more profitable rapid/express services*. Higher frequency services become more viable, with lower costs for rolling stock, infrastructure or personnel.

- *A better (integrated) product* to promote, of interest to more people, in more travel contexts and towards a higher number and variety of destinations.

- *Increased passenger flows and activity at or around (main) stations*. Increased land value if in possession to operators, higher opportunity or profitability for shops, services and facilities.

- *Improved effective capacity* of vehicles and stations from fewer (folding) bikes taken on-board.

Agglomeration benefits

A primary function of cycling-transit integration in our view is to help urban agglomerations maintain or reach high levels of accessibility, while still being able to accommodate rapid urban growth. A well-integrated cycling-transit system provides high accessibility between (sub-)centres and reduces dependence on cars. The second section discussed the mechanism by which accessibility from cycling-transit integration reinforces urban agglomerations by providing selective accessibility and liveliness for urban (sub-)centres and their extended surroundings. In contrast and unlike car-based accessibility, cycling-transit mobility steers away from distributive (sprawl) forces that work against the generation of agglomeration economies. We thus characterise the benefits for agglomerations as:

- *Improved accessibility*: Improved cycling-transit integration is a proven method of delivering efficient and scalable accessibility for residents and visitors, even under conditions of rapid urban growth and/or to accompany targets involving the curbing of car traffic.

- *Structuring urban areas:* Improved cycling-transit integration strengthens interconnected, poly-nuclear agglomerations, counters sprawl and leads to increased land value for extended areas surrounding sub-centres and transit stations.

- *Increased liveliness of public space:* Improved cycling-transit integration fosters safe, attractive, dynamic urban landscapes, increasing the attractiveness of cities.

- *Increased (inter)national competitiveness:* Improved cycling-transit integration is able to deliver mobility and accessibility that is compatible with and beneficial to safe, attractive and dynamic public space.

Conclusion

This paper identified six components of cycling-transit integration and discussed these in descending order of functional importance: a) Cycling and transit infrastructure and culture, b) Bicycle rental schemes, c) Bicycle parking facilities at transit stations, d) Integrated planning and operation, e) Integrated information and arrangements, f) Bike-on-board facilities and regulation.

Next we discussed how these components affect the land-use-transport system by seven mechanisms: a) Increased catchment areas, b) Increased choice (including station choice), c) Increased personalisation and customisation of transit journeys, d) Increased market base for rapid transit systems with more widely spaced stops, e) Increased competitiveness of transit, cycling and cities, f) Increased liveliness of public space and g) Increased agglomeration effects.

By these seven mechanisms we expect benefits for a) individual travellers, b) transit operators and c) urban agglomerations. As an example, we analysed the Dutch ‘bike-train’ system on each of the above components, mechanisms and effects.

We frame this systematic overview to illustrate how cycling-transit integration is a powerful, flexible and scalable strategy for urban mobility. Despite rapid growth in cycle-transit journeys in the Netherlands, hardly any dedicated data, integrated assessment, systematic research, integrated policy, integrated communication, value capturing or integrated investment exists on the issue, in the Netherlands or elsewhere. The available list of flexible and scalable mobility strategies for urban agglomerations is not a long one, while the quest for a sustainable, effective and efficient urban mobility is pressing. The Dutch case (and initial developments elsewhere) shows us that improved cycling-transit integration can deliver effective and efficient urban mobility whilst not just compatible with urban agglomeration economies, but actually symbiotically feeding such economies by means of the mechanisms discussed in the third section.

In part, the generation of such knowledge and its inclusion in local business cases, management, regulation, value-capturing or governance requires institutionalisation as an important component for achieving improved cycling-transit integration. Where we thus call for such institutionalisation in light of the urgent quest for integrated and sustainable urban mobility, an immediate application could be to test current projects and potentially their alternative variants for opportunities to include improved local cycling-transit integration as part of these projects and from there predict and measure how the subsequent effects manifest themselves locally for the actors involved, and integrate the lessons learned in further planning, management and governance.

Notes

1. *Second bikes* – Reference to bikes that a traveller might own and use at the non-home side of transit journeys (e.g. for travelling from the station to their workplace and vice versa). In the Netherlands in 2015, some 13% of egress travel is estimated to be made by bike. Some 85% of which are made by 'second' bike and the remaining 15% by rental bike ('OV-fiets').
2. *Increased weight of non-home trip sides* – If 20% of trips do not have a home side, it means that for each 100 transit trips, 20 of them have *two* non-home sides whereas the remaining 80 have both a home-side and a non-home side. The ratio then becomes (20*2+80*1) : (20*0+80*1) = 120 non-home sides versus 80 home sides of trips (+50%). Analysis of Dutch National Travel Surveys[8] and GPS-tracking data[12] indicates between 20%-33% of current transit trips don't have a home-side, implying there is 50% to 100% more non-home sides of transit journeys than home sides.
3. *Mesh-size* – when imagining all transit services to constitute a grid-like structure, the mesh-size refers to the average distance between parallel transit services (in a straight line). Typical values in the Netherlands would range from as low as 0.5 km in highly urbanised areas, up to 25 km in isolated rural areas.
4. *Transit segments* – based on average effective speed of a transit service[5].
5. *Speeds and lengths* – All speeds and lengths in this article are as measured by a straight line. The amount of service-km for a transit service is calculated as the sum of all straight lines between any of its consecutive stops (hence, excluding curves, detours, etc.). Speed of services is calculated by dividing the service-km total by the total ride time, defined as the sum of the difference between scheduled departure and arrival times of consecutive stops (hence, excluding halting times).
6. *Transit stop (area)* – 'Transit stops' in this document actually refer to stop areas. Stop areas combine nearby transit stop locations within a circle of 750m radius around a gravity stop having the highest number of transit services (neighbouring stops attached in a non-overlapping fashion with other stop areas). Stop areas serviced by less than 20 daily transit services are ignored[7]. 'Transit stops' are thus equivalent to areas serviced by at least one transit service per hour during at least 10 hours per day, serviced in two directions, be it train, metro, bus or ferry services that are nearby (not necessarily at one stop).
7. *OpenOv*http://www.openov.nl/ (www.openov.nl) – is an open data portal providing full specification of the entire Dutch transit system in an implementation of the General Transit Feed Specification, https://developers.google.com/transit/gtfs/ (GTFS). For this study, transit data was selected for an average work day, Friday December 16, 2016.
8. *National Travel Survey 2010-2014* – Own analysis of Onderzoek Verplaatsingsgedrag in Nederland (OViN). The total sample size over these five years is 585 294 trips as reported by 212 728 respondents for a random, pre-selected day of each year. Online data on http://statline.cbs.nl (search on OViN)
9. *Transit services* – The number of departing ferries, buses, trams, metro or trains. In case the same service can be accessed from multiple transit stops within the same catchment area, the service counts only once (no double counting).

10. *Budget-neutrality of OV-fiets* – In 2009, the OV-fiets scheme was institutionalised as a division of state-controlled Dutch Railways (NS). The OV-fiets scheme has been required to operate budget-neutral so that 'secondary' activities not impair with the subsidised activity of running trains.

11. *Bicycle parking investment schemes* – Masterplan Fiets' (1990-1997), 'Actieplan Fietsparkeren bij stations' (1998-present). See: http://mirt2015.mirtprojectenoverzicht.nl/Images/600_tcm341-358668.pdf

12. *Studio Bereikbaar pilot study on automatic trip detection* – Pilot study on automatic trip and mode detection conducted in December 2015 and May 2016, registering travel behaviour of 87 persons for around 28 days out of three sub-samples; first 47 pedestrian by-passers at the central rail station of the city of Eindhoven, second 28 respondents from a (randomly selected) participatory group in the drafting of a municipal transport policy by the city of Woerden and third a group of 12 employees working in a redevelopment area in the city of Rotterdam. In total, 13 332 trips were registered out of which 1 453 transit trips were observed using the Mobidot smartphone app (cf. Thomas et al, 2015).

13. *Access travel in GPS-tracking pilot study*[12] – wherever 'access' travel is stated in this context, we refer to either access or egress travel. In defining the 'main' mode of the combination of access and egress modes, we preceded car access over feeder access, then cycling access, then walk access. Trips 'accessed' by bicycle thus imply the bicycle is used at either side of the journey, while the respondent walked on the other side, or that cycling was used on both sides. Trips accessed by walking means the traveller was observed to walk on both sides of the transit trip. Walking was also implied for trips where no trip nor access or egress mode was registered or for displacements shorter than 500 m where trip detection is unreliable[12].

14. *Modal shares of trips to, from and in between cities* – Analysis of continuous Dutch National Travel Surveys[8] for example indicates how the modal share of cycling in trips 0-5 km towards urban locations (housing 2.5 M Dutch citizens) has risen from 32% to 40% between 2005 and 2014. Similarly, for transit trips longer than 25 km towards such 'urban' locations the modal share has risen from 30% to 38% between 2005 and 2014. Car use (as a driver) towards these urban locations has meanwhile dropped from 20% to 14% for distances 0-5 km and from 50% to 40% for distances >25 km in the same periods.

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