Synergies from improved bicycle-transit integration

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 ‘bicycle-train’ 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 bicycle-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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1. Introduction

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

There are chances too. Increasing densities and transformative developments together with growing economic and political power provide opportunities to align urban mobility needs with new mobility concepts. We also note how the continuing influx of urban dwellers and urban functions (despite rising housing costs in urban centres) at least implicitly indicates how car usage and car accessibility seem of reduced priority for cities. Where car travel is increasingly problematic and restricted to and from such locations, it does not impact the net 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.

Previous work on combinations of cycling and transit is relatively thin but is growing (Krizek and Stonebraker, 2010). Research 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 and 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 and Debrezion et al., 2009). The studies focus less on the underlying, distinct components and mechanisms that explain why and how cycling-transit integration functions. This article continues from the integrated perspective as presented by Krizek and Stonebraker (2010) and Kager et al. (2016a), focusing on the *synergistic* benefits that cycling-transit integration potentially leads to.

Section 2 explores the components of such a hybrid transportation system in practice. Next, section 3 discusses by which theoretic mechanisms synergistic benefits are created and for which parties. Section 4 assesses to what degree these components, mechanisms and synergistic benefits have materialised in the Netherlands by means of a case study. Finally, section 5 integrates the applied theory and results from the case study and discusses the allocation of synergistic benefits from improved bicycle-transit integration. Section 6 concludes and frames cycling-transit integration in light of the pressing quest for sustainable, effective and efficient urban transportation.

2. Components of bicycle-transit integration

This section reviews the practical components that determine the degree of bicycle-transit integration, while referring to Krizek and Stonebraker (2010) and Kager et al. (2016a) for a theoretic underpinning. Here, the focus is on the *functions* these components deliver for cycling-transit integration and why these are important for improving bicycle-transit integration. Aspects like the how-to, the how many, form, process or organisation are considered outside the scope of this article. For such aspects, we refer to the deliverables of the EU-funded 'BikeTrainBike' project (www.bitibi.eu/downloads.html).

2.1 Cycling and transit infrastructure and culture

Fundamental to cycling-transit integration - and the consequent achieving of synergies - is the local provision of safe infrastructure and culture to actually use either sub-mode (e.g. Martens 2004, Cervero et al 2012). Facilitating or even kick-starting either sub-mode is an issue for many cities or parts thereof. This is a topic outside the scope of this article. Nonetheless, where either one of both sub-modes is developed, we do think that cycling-transit synergy is a powerful strategy to let an existing sub-mode help leapfrog the other sub-mode in pursuing the expansion of both sub-modes. We believe this mechanism to work in many ways, including how facilitation of either sub-mode to some degree compensates partial physical or temporal absence of the other sub-mode, integrating opportunities where they arise into the business case of either sub-mode.

2.2 Bicycle rental schemes

Apart from such provision of infrastructure, we consider the provision of bicycle rental schemes the most essential component of cycling-transit integration. Bicycle rental has the potential to make bicycles available anywhere in an efficient way, in particular at the out-of-home location. By its nature, transit trips are generally undertaken to bring oneself outside the reach of one's home location and hence away from (actual or potential) individual bicycle ownership. It is thus we argue this destination part of transit journeys is most crucial to achieve cycling-transit integration, in line with analysis by various literature on the relationship between bike-sharing and transit (Griffin and Sener 2016, p.3, Fishman 2016, Ma et al. 2015, Jäppinen et al. 2013, Kaltenbrunner 2010, Martin and Shaheen 2014).

Transit journeys typically concentrating their destinations in urban (sub-)centres, it is for such locations we are most eager for space-efficient and flexible means of transport having low environmental impact. Also the business case for rental bikes works best here. Alternatives like letting travellers park a 'second bike'[1] on 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 importance of non-home locations and bicycle availability at such locations is finally leveraged by the considerable amount of transit trips which lack a home-side. Even in case just 20% of transit trips lack a home side, it means there is 50% more non-home sides of transit journeys than home-based sides[2].

The above arguments are much 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 argue that exactly for this reason the focus for cycling should be at the other, 'home' side of transit journeys. Where we first note how such reasoning does not alter the relative functions of the cycling component for both trip ends, also we think feeder services and cycling from a destination station serve distinct travel markets. Feeder services best serve 'thick' streams on somewhat prolonged distances, but limited in their number, cycling best serves 'diffuse' streams but high in their number. Also some people prefer sitting while being underway, highest safety, ride speed or comfort where other people prefer exercise while being underway, flexibility, individual adaptation or effective speed and reliability. We think either market segment should be accommodated for in order 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.

2.3 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 cycling rental scheme is not feasible. In urban (sub-)centres, we think 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.

2.4 Integrated planning and operation

Integrated planning and operation of both the transit and cycling system is instrumental to the other components and perhaps not a true component in itself. Nonetheless we consider it of crucial importance to make cycling-transit integration a success. Where the strongest effects of cycling-transit to our view are synergistic effects, i.e. outside 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 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, to frame rapid *transit as an extension to the cycling system* and as a crucial component of cycling policy intending to make an impact on urban accessibility. Where preferably such integration translates into a common organisation that plans and intervenes for either sub-mode, at least governments should adopt a common approach for both sub-systems in their planning, tendering and granting concessions and thus providing with interfaces for both worlds to connect.

2.5 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 space.

2.6 Bike-on-board facilities and regulation

The possibility to take a bicycle on board of trains in a reliable, hassle-free, cheap, fast and comfortable way (or similarly, on racks in buses) would probably constitute the best integration of cycling and transit for individual travellers. Unfortunately, we think this is utopia both for individual travellers and certainly for the transport system as a whole once more than a marginal percentage of travellers would follow the example. Bike-on-board lacks scalability because the space taken by a bicycle on board, but also the additional time needed to embark and disembark, or the additional space required in stations, on platforms, on stairs or elevators all make that bike-on-board can function only when used by relatively few. Accommodating for masses to use bike-on-board, transit will lose much or all of its cost-efficiency, space-efficiency, speed or comfort that constitutes its fundamental rationale.

We thus think bike-on-board should be regulated to not start working against cycling-transit integration or even general transit usage (cf. Krizek and Stonebraker, 2010). Having said so, bike-on-board can have a function in kick-starting cycling-transit integration, to increase ridership when and where slack capacity is available, to accommodate the movement of bikes on long hauls for single journeys and to temporarily compensate insufficient provision of other components. Apart from facilitation of such (niche) bike-on-board flows, we argue for containment and regulation as prime components of scalable bicycle-transit integration.

3. Mechanisms how improved bicycle-transit integration affects land-use and mode use

We present seven mechanisms how higher levels of bicycle-transit integration affects land use and travel patterns, thus preparing for section 4 and 5 which discuss how such changes in turn lead to synergies for travellers, transit operators and urban agglomerations. Ultimately all mechanisms are derived from cycling having the potential to be highly flexible, requiring limited private or public resources and having competitive speed 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. These limitations restrict general applicability or scalability for these modes whereas the bicycle mode lacks such fundamental limitations.

3.1 Increased catchment areas

The mechanism: Considering a typical cycling speed that is 3 times higher than walking (15-18 km/hr vs 5-6 km/hr), cycling can cover 3 times the *distance* in the same time, which in turn leads to a 9 times larger catchment *area* due to the quadratic relationship between radius and area. Where synergies between transit and cycling are considered, cycling is often framed as a means to increase the catchment areas of existing stations. Yet in spite of this understanding, we also note how the general issue of access and egress travel is often referred to as transit’s ‘first and last mile problem’ (or even as the ‘FMLM-problem’, e.g. Liu et al. 2012). When it is accepted that cycling potentially delivers large increases of catchment areas, such terminology is confounding the primary potential of cycling access.

The effects: The increase of catchment areas of existing stations quadratically connects more people and places to a given station or transit service. At the same time, the flexibility and public or private resources involved are theoretically comparable to walking. It is for this reason that we argue the same reasoning on increased catchment areas does not apply for car access or feeder access, even though these modes typically (though not always) offer higher speeds than cycling. Car or feeder access typically requires much higher resources paid for by the public or by their users, while not offering flexibility or scalability for travel routes and travel times with either high demand (cars) or low demand (feeder transit). In summary, cycling leads to extended catchment areas by a) its higher speed, b) the quadratic relationship between distance and area, and c) the high scalability and flexibility without requiring high marginal public or private resources.

3.2 Increased choice

The mechanism: The nine-fold increase in catchment areas compared to walking typically not just extends catchment areas but also introduces overlaps of the catchment areas of nearby stations. These overlaps get of particular interest when considering that transit services are typically based on a hierarchy where faster, more comfortable, more direct and/or more frequent services typically stop at selected, primary, stops only. Also the facilities of such stops can be much higher than those of transit stops lower in the transit hierarchy. Finally, intermediate cycling routes to each of the alternative stations in overlapping catchment areas might vary on many aspects. It is any such (intrinsic) variance within the transit system that makes overlapping catchment areas of high significance. No longer it can be counted upon that a near stop is selected by a traveller in case a cycling option lessens the tight distance constraint of walking.

Access or egress stops at elevated distances from the actual origin or destination may offer better matches for specific travellers or specific travel contexts. For this we note how acceptable walking time towards transit stops varies significantly, from say 500m for a local bus-stop versus 2.2km for an IC station (Keijer and Rietveld 2000, Wang and Liu 2013, p.117). Likewise we expect cycling catchment areas to vary from a typical maximum of 1.5 km to a local station to a typical maximum of 7.5 km towards an IC station (cf: Krizek and Stonebaker 2010). With such distances, also geographic topology gets an aspect to base choices on. 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 direct IC train uses at least comparable time to cover such (at least) 10.5 km compared to cycling the additional 1.5 km.

The effects: Because alternative transit stops and services cluster in and around urban centres, if not at walking distance than at cycling distance, the nine-fold increase in catchment area may cause an even steeper increase in choice. Steeply increased choice results in synergistic benefits by means of better matches in varying travel contexts or under varying traveller preferences or by means of increased resilience against 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 steeply increases (individual) choice on how to use the transit system and hence its adaptability to varying travel contexts and individual preferences.

3.3 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 like walking or car access. However, the above mechanism of steeply increased station choice also allows for effective customisation of the ‘transit’ part of the journey: which station is selected (and which ones are not), which services are used (and which ones are not), 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.

The effects: Increased customisation of transit allows travellers to better upkeep 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 crowdedness or reliability of a service. In such situations, high use of cycling can lead to improved, self-organising distribution of travellers and better use of slack capacity, provided information on such aspects is somehow shared or otherwise known to travellers. Derived from this may come higher satisfaction, willingness to pay, use frequency or a higher utilisation of additional services.

3.4 Increased market base for rapid transit systems at prolonged distance

The mechanism: A second mechanism invoked by the larger catchment areas and higher choice is that cyclists will typically prefer *rapid* services and their stations (Krizek and Stonebaker 2010). Because rapid transit stops are not and cannot be offered at low mesh-sizes[3] they -on average- can only be accessed at a higher distance from average, random origins and destinations. In such terms, the typical deal offered by cycling as an access mode is to bypass a nearby stop or station at a walkable distance but that offers slower transit service, and instead cycle to a stop or station that offers rapid services. In such way, and typically so for prolonged distances, 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 lend the bicycle. However, the traveller saves on fares, saves on travel time and avoids potential unreliability of the feeder service that could cancel the connection at the transfer station. Also the traveller saves one or more transit transfers and perhaps circumvents the unavailability of the feeder service at the moment it is needed. This mechanism leads to increased *relative* market share for rapid transit and/or transit travel at prolonged distances. Secondary, where alternative stations serve alternative rapid services (for example in different wind directions), cycling is capable of sorting out travellers to the right station, thus delivering a ‘magic hand’ to sort out travellers to and from the right rapid service as long as these are offered somewhere in the vicinity of travellers’ final origins or destinations. Finally, for areas where no feeder transit exists or is feasible, cycling can function to complement an isolated stop and increase the effectiveness of rapid transit lines there.

The effects: Increased demand for rapid transit systems can improve their business case, so they can be offered in higher frequency, in lower mesh-size[3] or in higher variety. When and where this happens (we think the extensive Dutch national IC-rail system is an example of this, as discussed in section 4), 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 (indirectly also feeding feeder systems).

3.5 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 get more attractive, we expect people also 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 desired locations for many, 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 their (urban) destinations, 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).

The effects: First of all, higher transit competitiveness maintained over extended areas increases the likelihood of individuals using it more often for their existing travel behaviour, or in being less likely to shift away from it. By nature of the transit system, such locations are highly selective and localized; namely the surrounding areas of (rapid) transit stops or areas within the effective catchment area of such stops. These locations are typically 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 possession 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 in a recent German study that showed how people moving new into a city that is transit or cycling-friendly were likely to adopt multi-modal mobility practices, even if coming from origin cities lacking such mobility options, while measuring how this likelihood was higher than for people adopting 'mono-modal' mobility practices when moving in opposite direction to mono-modal cities (Klinger, 2017).

3.6 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, in varying travel contexts, leading to *more access and egress journeys* either by foot or by cycling.

The effects: A growing body of literature highlights how an increased number of 'faces in the street' makes urban space be considered safer and more attractive. The number of people to look at, eye contact, the feeling exposed to other people, all increase a feeling of belonging and being connected to a place and its people, hence contributing 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' (Gehl, 2010).

3.7 Increased agglomeration effects

The mechanism: Accessibility by transit and/or by cycling is highly distinct from accessibility by car travel. For car travel, distance is the key factor determining accessibility. The typical provision of fast highways - in positive correlation to urbanity - somewhat stretches distance deterrence towards urban areas, but this is much countered by (chance of) congestion and slow urban traffic once off the highway, either effect in positive correlation to urbanity too. These and similar counter-effects often render accessibility by car relatively geographically neutral in practice. This is quite different for transit and cycling. Transit is highly geographically selective. Availability, speed, frequency and comfort are all highly dependent on the urbanisation level of *both* the origin and destination of a trip. And for cycling, sensitivity to distance is very high, including a practical limit on acceptable distance for most travellers. This renders the accessibility options by a bike particularly of interest for the area surrounding the home location and/or external locations reachable by other transport means. The derived accessibility options for cycling are thus typically much more of significance in cities, because in cities the limited catchment areas contain high densities. Cycling and transit-based accessibilities are thus primarily influenced by the urbanisation level of both origin and destination, not primarily by distance.

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 only found in cities (where densities are usually strong already), bicycle-transit integration tends to reinforce poly-nuclear structures of separated densities rather than random concentrations of people and functions. Such networks are characterised by having both 'centrality of distant connections' favouring even more transit (Amin and Thrift, 2002) as well as increased nearness favouring even more use of active modes, (cf. the concept of 'immotility', Ferreira et al., 2017). Exactly such spatial patterns have been identified a key success factor for agglomeration economies (e.g. 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 (cf Urry, 2007, p.120, Merriman 2009); cycling-transit integration fosters opposite land-use patterns, namely poly-nuclear (sub-)centres at intermediate distances, favouring agglomeration economies.

The effects: By improving the interconnectedness of sub-centres, their relative strength and their area of influence, also the number of opportunities increases for people and services to find a place in their habitat niche of the urban system; a location offering precisely the right accessibility level at the right cost. Organisation of land-use in such a way also facilitates trip-chaining by combining activities around sub-centres and transfer locations, in turn increasing chances for secondary functions.

4. Case study: bicycle-train integration in the Netherlands

We now analyse the integration of cycling and transit in the Netherlands. Both modes are highly used: for cycling, some 28% of all national trips are made by bicycle, equalling 10% of all national km travelled and 21% of travel time. Transit accounts for 5% in daily trips, 12% of km travelled and 13% of travel time[8]. In particular, and out of a total population of 17 million, around three million citizens who live or frequent the (sub-)centres of the Dutch urban agglomeration, combined use of cycling and transit has surpassed the car-system as their primary transportation system[8].

For the Dutch transit system, the train mode is a quasi-monopolist in delivering rapid transport over elevated distances. Table 4.1 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 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 4.1. **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 consequent stops[5]. Source: www.OpenOv.nl[7]

The above theory suggested how cycling and transit deliver disproportionally higher benefits when cycling is combined with rapid transit services. Indeed, the national share of the bicycle is 47% in access travel and 13% in egress travel to train stations whereas 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 bicycle-*train* integration as representing the typical case of bicycle-*transit* integration for the specific case of the Netherlands.

4.1 Components

We provide an overview of the components of cycling-transit integration in the Netherlands according to their specification in section 2. For this, we present three key observations (in descending order) on distinct aspects that to our view best describe the maturity level per component. For each observation we grade how this (counter-)indicates maturity using a qualitative scoring of **(+)**, **(0)** ,**(-)**.

- *Cycling and transit infrastructure and culture*: a) Infrastructure and culture for cycling is at a high level in the Netherlands, especially for inner-urban cycling (Harms et al. 2015). It is by such infrastructure that cycling has the highest modal share for all Dutch trips till 7.5 km (national average: 34%, inner-urban average: 45%). Cycling also typically is the fastest travel mode up till 3 km which is the average length of a cycling trip **(+)**. b) For intercity rail transit, on average there is at least four rapid intercity rail services per hour between the most important towns, having average market shares of over 70% for travel between their centres[8] **(+)**. c) Furthermore, more than 60% of the Dutch population has a positive attitude towards cycling (Harms et al, 2016) **(+)**.

- *Bicycle rental schemes:* a) Many cities in the world have recently developed extensive and successful public bicycle rental schemes (e.g. Fishmann, 2016) but very differently so in the Netherlands. Other than in most other countries, public bike rental in the Netherlands is almost exclusively related to train stations and geared towards domestic train travellers only. This 'OV-fiets' system has consistently grown by 20% to 100% on a year-to-year basis since its small-scale introduction in 2004 and now boasts 12.000 bicycles, 300 hire locations and 2.5 million rentals per year in 2016 **(+)**. b) However, despite year on year extensions, demand exceeds supply on most days, making the scheme in current form unreliable especially for large stations with high rental rates **(-)**. c) Also, pricing of the bike is inflexible - 24hrs-blocks only without flat-rate subscriptions or discounts possible - while the rent price has risen by over 50% since its introduction. This, in conjunction with the continuous rapid extension of the scheme, suggests there is high latent demand for the cycling scheme, most likely increasingly so under potentially different pricing configurations. On this, the extreme difference in cycling levels in access transport (47%) versus cycling levels in egress transport (13%) where the 'OV-fiets' scheme just delivers around 1.5% out of this 13% is a major indication that despite its rapid and continuous expansion, its potential is underutilized (cf. Kager, 2016b) **(0)**.

- *Bicycle parking facilities at transit stations:* a) Orders of magnitude larger than the bicycle rental scheme, bicycle parking at rail stations is a big affair in the Netherlands, and easily the most visible aspect of its cycling-transit integration. All in all 2015 sees some 500.000 bicycle parking places distributed over any of the 410 Dutch train stations on a population of 17 million and 1.3 million train travellers per day **(+)**. Also there generally is a choice between guarded and unguarded parkings, paid and unpaid and with separated bike parkings at most or all multiple entry/exit points of stations **(+)**. Recently, an extension scheme was agreed upon for roughly another 100.000 bike parking places to be completed before 2020. Apart from quantity, large scale replacement schemes have raised and standardised bike parking quality during the last two decades and are still ongoing **(+)**.

- *Integrated planning and operation:* a) Despite the fact that the dominant access mode of the Dutch train system is by bicycle and despite the fact that most transit users in the Netherlands are active cyclists too (just because the majority of the population is), the worlds of transit and cycling are nonetheless highly separated when it comes to government, organisation, lobby, data, research, planning, monitoring and debate **(-)**. b) The autonomous, bottom-up, growth of around 4-5% nationally and annually in journeys involving both cycling and transit since 2005 seems to offer many chances and strong rationale for active and integrated involvement. **(0)**. c) In particular the planning of new stations, changes to timetables, major new cycling routes and other elements of transit and cycling policy are still uncoordinated, although the rigid separation between both worlds seems to be diminishing and the near future might see breakthroughs here **(0)**.

- *Integrated information and arrangements:* a) Similar to the limited integrated planning and operation, the Netherlands shows only limited development on this aspect. Cycling-inclusive travel planners from door-to-door are either lacking or are under-developed, where arrangements to combine cycling and trains are virtually non-existing **(0)**. b) However; there have been explicit marketing campaigns promoting the flexibility of the 'OV-fiets' rental scheme in conjunction with train travel by the Dutch Railways, accompanied by a combined offer, and the Dutch rail planner states 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 **(+)**. c) Nonetheless, for students, tourists, or frequent travellers, no targeted cycling-inclusive arrangements exist. As a counter-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:* a) In comparison to bike-parking and bike-rental, bike-on-board is both limited and restricted (forbidden during peak hours, requiring a flat EUR 6 fee when it is allowed, only a handful of places available per train). Statistics of bike-on-board are non-existing, but comparing effective bike-on-board capacity to train travel intensity, less than 0.2% of all train journeys involve a bike on board. Roughly the same applies for folding bikes that can be taken on board everywhere, free of charge and also during peak hours, but still spotted occasionally at most. 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 **(+)**. b) At the same time, 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 **(+)**. c) All in all, both bike-on-board facilities as well as its regulation seem in balance and deliver their (niche) function **(+)**.

4.2 Policies and expectations

- *Cycling and transit infrastructure and culture*: a) The Netherlands has a long tradition of providing high quality infrastructure for cycling and transit. Apart from its high usage, this is reflected by relatively strong institutions and general support for (especially) the Dutch cycling culture and appreciation of cycling infrastructure **(+)**. b) Policies aim at delivering high quality cycling and transit infrastructure based on explicit standards and from an inclusive engineering culture where infrastructure budgets are constant or increasing **(+)**. c) Relevant for this article however is that investments in cycling and transit infrastructure and culture have not typically been expected to make a contribution to any cycling-transit synergies. Similarly, the providing of route infrastructure is typically not connected to synergistic opportunities or policies to increase cycling-transit integration **(0)**.

- *Bicycle rental schemes:* a) As noted above, an easy-to-use cycling rental scheme that can be used in conjunction with local transit was introduced in 2004 only, despite the fact that such schemes by then already existed in many urban regions outside the Netherlands, and despite the fact that since long combined use of cycling and train has been high for access travel, but quite low for egress travel. This at least indicates there could be a significant market potential on the non-home side of train journeys where availability of one's own bike is much reduced, but which potential was never tapped from till 2004 **(0)**. b) In this light, we note that the successful introduction of the OV-fiets was initially a private initiative which - although receiving limited subsidy in its pilot phase - never had been planned for by active policy intervention. Also looking back on its steep and consequent 20% till 100% annual growth rates since its introduction, this high success was barely envisioned, understood or investigated and until today is hardly integrated in business cases or policy development **(0)**. c) At the same time its 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] **(+)**.

- *Bicycle parking facilities at transit stations:* a) Increasing both quantity and quality of bike parkings at train stations has been an active programme since the 90's and paid for jointly by national and local governments. The current phase between 2013-2020 totals E 221 mln for some expected 100.000 additional bike parking capacity[11] **(+)**. b) 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. However, with rising costs due to increasingly complex station surroundings and exploding cycling numbers, planning, financing and operation of the facilities is increasingly problematic. Furthermore, it remains undecided who should pay for them and by which share. Policy seems insufficient to smooth such continued discussions for next investment phases, for running and replacement costs and for projects that did not make it into the scheme or in connecting benefits to investment costs **(0)**. c) In the same time, the capacity of many facilities is filled up for over 80% by so-called 'second-bikes' as many use them for egress transport [n1]. Where these travellers only make up 13% of transit journeys, due to their extended parking times, their bicycles require higher parking capacity compared to the current 47% of travellers *accessing* a station by bicycle. This indicates a disbalance in the expectation of the parking facilities offered and their actual, predominant use **(0)**.

- *Integrated planning and operation:* a) The above provision of infrastructure, cycling rental schemes and bike parks so far has lacked clear consideration of cycling-train synergies and its associated synergies as part of its business case or its decision making process **(-)**. b) Infrastructure is built or adapted where land-use is changing, where safety issues exist or to increase speed, comfort or directness of routes. In the last decades, new bike parks at stations have been proposed where existing ones were insufficient, 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 seemed foremost due to the absence of regulations, tradition, tools, concepts and methodologies (like TOD) or even awareness of the option to actually do so, despite cycling being the main access mode of train travel in the Netherlands since long. This practice can be both explained by the fact that cycling-transit synergies are typically not made explicit, anticipated, analysed, measured or evaluated. **(-)**. c) A second reason for lacking integrated planning and operation seems the high segregation between their planning organisations, planning cycles and funding or tendering schemes, where no interfaces or other arrangements have been pursued to connect the two. Although steps in this direction have thus been few and limited, recently new initiatives have emerged, including putting the subject high on the agenda as part of the Dutch 'Bicycle Agenda 2017-2020' by all Dutch governments layers and partner organisations (Tour de Force, 2017) **(0)**.

- *Integrated information and arrangements:* a) The arrangements mentioned in section 4.1 mostly stem from the fact that both the national 'OV-fiets' public rental bike scheme and many bike parkings are subdivisions of Dutch Railways (NS), and for this reason **(0)**. b) However, where in such settings we observe some integration of information and arrangements, the rationale of such integration and their offerings seem more targeted to increasing use of the (sub-)mode, but much less so in anticipating, actively monitoring or steering on synergistic effects **(-)**. c) Active policies from government on this aspect are virtually unknown, also as a consequence of the persistent high segregation between the transit and the cycling worlds, although changes seem underway in response to increasing awareness that the current separation fails to incorporate synergies (cf. Tour de Force, 2017) **(0)**.

- *Bike-on-board:* a) In light of train-cycling integration, the biggest achievement is that bike-on-board is effectively (self)-regulated; allowing the bike-on-board option for a few, whereas most bike-train users seem to agree at least implicitly with just that **(+)**. b) In addition, we note the current preparation of most Dutch high-speed trains to allow a limited number of 4 bicycles per train like most other trains **(+)**.

4.3 Effects and trends

We next illustrate effects for travellers, transit operators and agglomerations by taking a closer look how various segments of the transit system connect to where people live on a walking distance versus a cycling distance. For this purpose, we adopt a subdivision of the transit system as in table 4.1 based on average speed of transit services.

- *Increased catchment areas*: Table 4.2 illustrates for the Netherlands how walking and cycling connect which share of the Dutch population to transit stops. Where 79% of Dutch population has a transit stop serviced by at least 20 daily services[6] within a walkable distance of 1.25 km or less, this percentage increases to 98% for a cycleable distance of 5 km or less[5]. Thus, for areas with sparse transit services, the bicycle is capable of connecting 98% of the whole population to at least one transit stop within 5 km, where walking connects 79%, thus leaving out 21% of the Dutch population. The (relative) importance of cycleable distances gets higher 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 4.1), we see that a small minority of 10% of Dutch population lives at a walking distance from these stops. For a cycleable 5km we see this percentage rising to 46% for exactly the same 365 locations. <u>The bicycle thus substantially extends the catchment area of transit services in the Netherlands, but in particular for services of higher operating speed. The bicycle connects roughly five times more Dutch citizens to express transit services compared to walking (46% vs 10% of the Dutch population).</u>

Table 4.2. Catchment areas of transit services, by transit segment and (max) distance to stop

Transit segments[4]	**< 1.25 km (walk)**[5]		**< 2.5 km (bike short)**		**< 5 km (bike long)**	
	coverage	# services[9]	coverage	# services	coverage	# services
Local or faster (any speed)	79%	429	93%	756	98%	1.233
Hybrid or faster (>30 km/hr)	51%	186	79%	282	93%	435
Rapid or faster (>40 km/hr)	19%	165	44%	213	63%	286
Express (>60 km/hr)	10%	133	28%	159	46%	202

Note: Distances and speeds measured in a straight line[5]. Coverage as percentage of Dutch population (17 mln). #services specifying access to unique transit services[9] within the catchment area. Source: **Error! Hyperlink reference not valid.**[7]

- *Increased choice* : Table 4.2 also specifies *how many* daily transit services can be accessed from any transit stop 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[6]). We can thus observe how cycling not just provides opportunity for 46% of the Dutch population to access express transit (versus just 10% for a walkable 1.25km), but that this 46% can actually choose from 202 such daily transit services[9] on average versus a significantly lower 133 services for the 10%. Not shown in the table, but as it can be induced, these services are spread on average over a higher number of transit stops where these services can be accessed from. The bicycle thus connects people *who are connected* to express transit services by an additional 52% *more* daily express services compared to walking (202 vs 133). Contrary to the hub-and-spoke philosophy that sometimes is assumed intuitively in its design or analysis, the Netherlands thus offers a clear case where access to just one near station that hosts such express services on average does not mean this station hosts *all* such express transit services in the near vicinity.

- *Increased customisation of transit journeys*: The above alternative stop locations to access an increased number of transit services can be spread in a circle with a radius of 5 km and potentially in any wind direction. Different stations might offer different facilities and services, the route towards these stations might differ in many aspects, and also topology gets a meaningful factor; two stations can potentially be 10km apart which easily might constitute a significant part of the transit journey itself. It is by such mechanisms that the bicycle in the Netherlands not just increases choice on the amount of accessible services, but also provides a meaningful choice on alternative stations and hence their facilities, on the intermediate routes taken or their opportunities for intermediate stops or combining activities, or on alternative configuration of the transit journey (e.g. varying in remaining distance, required number of changes, frequency of services or amount of backup options).

Table 4.3. Catchment areas of transit services by transit segment and (max) 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)**	
	coverage	# services[9]	coverage	# services	coverage	# services
Urban (NL pop = 2.3 mln)						
Local or faster (any speed)	99%	1.777	100%	3.858	100%	6.264
Hybrid or faster (>30 km/hr)	61%	546	94%	1.004	100%	1.746
Rapid or faster (>40 km/hr)	39%	342	77%	578	96%	906
Express (>60 km/hr)	25%	227	64%	348	89%	522
Rural (NL pop = 3.6 mln)						
Local or faster (any speed)	60%	108	83%	179	95%	347
Hybrid or faster (>30 km/hr)	42%	87	65%	117	86%	183
Rapid or faster (>40 km/hr)	9%	82	22%	96	42%	126
Express (>60 km/hr)	3%	66	9%	73	21%	96

Note: Distances and speed as measured in a straight line[5]. Source: **Error! Hyperlink reference not valid.**[7]

- *Increased demand for rapid transit systems:* The years between 2005 and 2015 showed significant growth of public transport use (+22% train passenger-km, KiM 2016). Where also the share of cycling as an access mode for these increased flows grew from around 30% in 2000 towards 47% in 2015 (Kager et al. 2016a), cycling towards stations grew even harder than transit flows. At the same time, investments in the network, increase of travel volumes and increase of bike flows have not been evenly distributed over the network. Six major sections of railways have been converted from two to four tracks and a high-speed line was introduced, invariably on the direct routes between the top-5 of Dutch cities. Also all of the central stations of these cities have been renovated, ameliorated and expanded. The new capacity was mostly used to increase additional fast, IC-services and/or to make IC's run faster. This pattern is repeated in elevated growth of cycle volumes to and from IC stations, versus relative 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 stretching 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. Effectively these trends concentrate an increasing portion of travel movements (at least in relative shares) to a smaller number of rapid services and their stations. Considering the high cycling shares favouring exactly these lines and stations of up to 65% in access travel (where cyclists could have chosen other nearby stations or services), cyclists followed these trends and thus helped the success of the underlying policies.

- *Increased competitiveness of transit, cycling and cities:* Key for this mechanism is whether or not bicycle-train 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 for Amsterdam the population growth in the past decade has compensated the population decline since the 1960s (CBS Statline, 2017). This all is typically combined with a gradual but consistent increase of restrictions imposed to the local car system (traffic calming, 30 km zones, street closures, traffic comparting, reductions of parking capacity, increasing parking tariffs, banning of polluting cars etc). To foster the claim that bike-train synergies are condensed into such locations, table 4.3 reproduces table 4.2 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 4.3, 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 4.3 in comparison with national averages in table 4.2. From these comparisons, we argue how bicycle-train 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. (cf. Fleming 2016)

- *Increased liveliness of public space:* The Netherlands features many mid-size cities with intact historical centres. Where these locations are typically prime examples of lively, attractive and high-valued public space, most of them also have a major rail station nearby. How much walking and cycling towards and from such stations contribute to this liveliness hasn't been measured, but provided the high amount of daily train travellers and the high modal shares for walking and cycling in access and egress travel is an indication such trips significantly influence liveliness. As an initial estimate of such degree, a pilot study on automatic trip detection discussed in section 4.4 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 on this effect all operate on a long time scale and are complex to analyse in isolation. We do note however that where the Netherlands is renowned for its high cycling levels, also its extensive train system and its poly-centric urban structure are prominent characteristics of the Dutch land-use/transport system. Where roughly since 2005 many of these poly-centric cities share in the trend of urban densification and urban expansion, so too have cycling levels within such cities (Harms, 2014) and train use to and from these cities[8]. Finally, analysis of Dutch National Travel Surveys reveals that both such cycling levels and train use not just rises proportionally to urban growth, but also sees its *relative* modal shares increasing[8].

4.4 Bicycle-transit trips measured using automatic trip detection

To supplement the above high-level analysis, we complete the case study by looking at detailed and factual transit usage, albeit from a small (and perhaps 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-based trips. From this sample, we observed roughly as many transit trips based on cycling access[13] travel (45% of all train trips) compared to pedestrian access (21%) or without a trip recorded (15%, access or egress trips shorter than 500m could not be recorded due to detection method).

Table 4.4. **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 500m 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 either segment was that the average ride speed of a train when used after being accessed by bicycle equalled 79 km/hr versus a significantly lower 69 km/hr when the train was accessed by walking. For this, stations accessed by cycling access were observed to be selected by means of an average 2.1 km bike ride in a straight line (2.8 km by road) instead of an average 1.1 km observed for walk trips (1.2 km by road) while noting that trip segments shorter than 500m have not been detected and hence cause an elevated 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. We expected such selection of more distant stations to be mostly of interest when travelling extended distances. Indeed we measured how train journeys involving a bicycle were 34 km long (in a straight line) versus 27 km for train journeys involving walk access. Table 4.4 summarizes these and some other key statistics of these observed journeys.

Finally, table 4.5 analyses how respondents with non-marginal transit use (2 or more transit journeys per week on average, as reported by 60% of the sample) reported distinct transit usage based on their levels of using a bicycle to travel to and from rail stations. For this, we subdivided the remaining sample in three segments based on the amount of cycling trips for access or egress travel. The third with highest bike usage on average reported 13.3 weekly transit trips (52% of which involved a bicycle) 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 bicycle), 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 4.5. **Weekly transit usage, 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]

5. Synergies from improved bicycle-transit integration

This section summarizes the above effects from increased cycling-transit integration, details more on how these effects lead to synergies and allocates them to their beneficiaries. In the discussion we combine theoretic understanding of the mechanisms as described in section 3 with observations in practice from the case study in the Netherlands in section 4 which in turn involved analysis of the Dutch transit system in conjunction with Dutch (urban) geography in section 4.3 and analysis of three pilot studies on automated and anonymous trip detection in section 4.4.

Commenting on and summarizing the above discussions, we argue that it is difficult to link specific investments in bicycle-transit integration to specific benefits because of:

- conceptual complexity
- variety of distributed components and effects

- components and effects interacting on different geographical scales, time scales and by means of varying threshold levels
- limited data availability and
- the relative novelty of interdependent urban growth, increasing transit ridership and emergent cycling.

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 bicycle-transit integration (cf. section 2.4). Where we thus call for such institutionalisation in light of the urgent quest for integrated and sustainable urban mobility, an immediate application of the effects below could be to test *current* projects and potentially their alternative variants for opportunities to include improved local bicycle-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.

5.1 Traveller benefits

For travellers, section 4.3 illustrated how combining cycling and transit provides opportunity to access a higher number of transit services - in particular rapid services - both in their availability and in their choice where available. On average, we expect this to deliver faster and/or more customised transit journeys if more distant stations can be accessed by bicycle. From section 4.4 we observed that indeed individuals who used a bicycle selected transit that travelled on average with 15% faster ride speed than transit accessed by walking.

Provided that table 4.1 illustrated how virtually any Dutch person is connected to (at least) basic transit within a walkable maximum of 1.25 km from the home location, the cycling trips are motivated by choice rather than by necessity. Considering that in the Netherlands 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) we also observe significant growth of the total number of train travellers and e) we observe high numbers of people parking or renting a bicycle at many stations (in spite of congestion, see section 4.1), we deduce that individual travellers experience high and consistent (net) benefit from this cycling-transit integration. We note how these benefits are *synergistic*; they 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 (cf. Kager et al., 2016a). In summary we conclude that travellers benefit from bicycle-train integration by various aspects:

- *Travel time savings:* Travellers can use faster services (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 the bicycle as an access or egress mode.
- *Personalising journeys:* Travellers can select their own departure time, cycling route, intermediate (stop) points or sub-destinations, (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 the bicycle instead of other access modes can experience a significant net increase in travel options to or from certain locations, in particular for locations where other travel options are becoming more 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.

5.2 Transit operator benefits

Although transit and cycling are sometimes framed as competing against each other, in particular feeder transit services, both in section 3 and section 4 suggest there in fact is a (net) synergistic benefit from increased cycling for both feeder transit and for rapid transit. For this, first we note how the Dutch transit system at either level is at least as good as it is found in most comparable urban agglomerations (in proportion to size and density) 'despite' high cycling levels. This implies that where competition between cycling and transit might perhaps exist on the *trip (segment) level*, this competition does not manifest itself at the level of the transport system as a whole, nor even at the level of individual travellers when comparing their overall travel behaviour and controlling for cycling rates (see section 4.4).

We believe that from the transit operator's point of view, it is not ultimately just about transporting as many travellers as far as possible. It is also about how much effort is needed to accommodate these flows. For transit, this translates quickly to the question of aiming for 'thick' streams: concentrated travel flows by a sufficient number of passengers (the transaction base) over a sufficient distance (the fare base) while avoiding cost components such as halting times, non-straight routes, speeds below economic base speed. From such a perspective, cycling offers a 'magic hand' to transform parts of diffuse travel patterns into more neatly organised concentrations of travellers at the right stations, travelling in more concentrated flows to other connecting stations while requiring less in-between stops. This could lead to reduced material cost, personnel cost, infrastructure cost, and at the same time increased reliability, ridership and willingness to pay. Evidence from the Netherlands, where bike-train ridership has grown strongly, suggests that this growth may not undermine ridership or efficiency of *existing* feeder transit services, which provides coverage for those unwilling or unable to cycle to stations, but is also used regularly at the 'other' access or egress segment of a trip involving rapid transit and one cycling trip-segment, and/or is used by frequent cyclists who use feeder transit for a lower *proportion* of their (rapid) transit trips, but compensated by them making *a higher number* of (rapid) transit trips (cf. section 4.4).

In addition to these considerations, section 4.4 indicated how travellers who made above-average use of cycling in conjunction with transit, made 75% more trips by transit (travelling 67% more km), while train trips accessed by bicycle operated at a 15% higher average ride speed (79 km/hr vs 69 km/hr) and was used for a 29% longer distance (43 km vs 33 km). We characterise therefore the synergistic benefits from cycling-transit integration for transit operators as:

- *More concentrated and (self-)organising 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*. More miles in the same time: higher frequencies possible, lower cost on 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 and services.
- *Less (folding) bikes on board and in stations*

5.3 Agglomeration benefits

A primary function of cycling-transit integration in our view is to help urban agglomerations maintain or reach high levels in accessibility, while able to accommodate rapid urban growth. This includes in particular high accessibility between (sub-)centres and reduces dependence on cars. Section 2.5 discussed the mechanism how accessibility from cycling-transit integration also reinforces urban agglomerations by providing selective accessibility and liveliness for urban (sub-)centres and their extended surroundings. Unlike car-based accessibility, cycling-transit mobility steers away from distributive (sprawl) forces that work against the generation of agglomeration economies. We thus characterize the benefits for agglomerations as:

- *Improved accessibility*: Improved bicycle-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 bicycle-transit integration strengthens interconnected, poly-nuclear agglomerations, counters sprawl and leads to increased land value for *extended* areas surrounding transit stations
- *Increased liveliness of public space:* Improved bicycle-transit integration fosters safe, attractive, dynamic urban landscapes, increasing the attractiveness of cities
- *Increased (inter)national competitiveness:* Improved bicycle-transit integration is able to deliver mobility and accessibility that is compatible with and beneficial to safe, attractive and dynamic public space.

6. Conclusion

This article identified 6 components of bicycle-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 affects the land-use transport system by seven mechanisms: a) Increased catchment areas, b) Increased choice (including station choice but not limited to just station choice), c) Increased personalisation and customisation of transit journeys, d) Increased market base for rapid transit systems at prolonged distances, 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 these successes, hardly any dedicated data, integrated assessment, systematic research, integrated policy, integrated communication, value capturing or integrated investment exists on the issue, neither in the Netherlands nor abroad. 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 bicycle-transit integration can deliver for urban mobility whilst not just *compatible* with urban agglomeration economies, but actually symbiotically *feeding* such economies by means of its specific seven synergistic mechanisms.

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 does 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 urbanized areas, up to 25km 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 subsidized 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 Dec 2015 and May 2016, registering travel behaviour of 87 persons for around 28 days, constituted by pedestrian by-passers at the central rail station of the city of Eindhoven, a randomly selected participatory group in the drafting of a municipal transport policy by the city of Woerden and 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, adopting 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 the bicycle 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 500m 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 2.5mln Dutch citizens) has risen from 32% to 40% between 2005 and 2014. Similarly, for transit on trips >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 0-5km and from 50% to 40% for distances >25km in the same periods.

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