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Effects of upgrading to cycle highways - An analysis of demand induction, use patterns and satisfaction before and after

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A R T I C L E I N F O

Keywords:
Cycling
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Infrastructure upgrade
Induced cycling
Weather
Temporal profile

A B S T R A C T

Objective: The objective of the present study is to investigate the effects of improvements made to two large, interconnected bicycle infrastructure in the western suburbs of Copenhagen, Denmark, on bicycle volumes and mode share, and cyclists' behaviour, perceptions, and experiences.
Methods: Effects are assessed by analysing data from automatic counting stations during 35 months to measure the changes in bicycle volumes on the investigated routes. Furthermore, a questionnaire survey repeated three times – before, and one and two years after opening the improved routes - is used. Findings are supported by a control survey at a nearby facility, which was not influenced by the infrastructure improvements.
Results: The investments related to the two investigated cases of infrastructure improvements resulted in a significant increase in the volume of bicyclist two years after the improvements. On one of the routes, the "Albertslund Route", on weekdays during the rush hour in daylight, an increase from 126 to 203 bicyclists/h was recorded, whereas an increase from 24 to 32 bicyclists/h was recorded at "Vestvolden" for the same period. Most of the increase could be attributed to relocation of bicyclists from other routes. Induced cycling trips – trips that were not previously made by bicycle - were estimated to account for only 4–5% of the bicyclists two years after improvements. Bicyclists using the improved route express an increase in satisfaction with the quality of the facilities, which is significantly higher than at the control site.
Conclusion: Data from the counting stations provides useful information if measured over a long period. This is necessary to correct for factors such as climate effects and temporal variation. Investments in cycle infrastructure in the investigated case led to a higher number of bicyclists who were mainly relocated from other routes. A minor increase in the modal share of cyclists was observed two years after the infrastructure improvements. Furthermore, the investments resulted in a higher degree of satisfaction among active bicyclists. If measured over a longer period, this could lead to a higher modal share due to a potential social advertising effect.

1. Introduction

The promotion of cycling has gained increased political attention as an alternative to commuting by car both to avoid congestion because of environmental concerns and to increase individuals' physical activity and thereby health (see, for instance, Krizek et al., 2009; Ogilvie et al., 2011). Policy initiatives that aim to increase the modal share of bicyclists through improved urban design/infrastructure have been implemented in many cities around the world (see, for instance, Dextre et al., 2013) – both in smaller towns and cities (Handy et al., 2012) and in megacities (Pucher et al., 2012). Improvements to bicycle infrastructure are regarded as the main instrument to achieve such a goal (Parkin and Koorey, 2012). However, the crucial policy question is how good an instrument it is. This leads one to question which behavioural changes may result, and how they should be measured. This paper addresses this question based on *ex ante* and *ex post* user surveys and detailed longitudinal analysis of flows on a cycle highway and a cycle greenway project in Copenhagen in Denmark.

Following SACTRA (1994) and Hills (1996), increasing infrastructure capacity or improving its quality may influence the total volume of activities, their location and timing, the mode of transport used, coordination of activities by different individuals as well as the route

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chosen. More recent studies have addressed specific challenges when assessing investments in bicycle and pedestrian infrastructure (Krizek et al., 2009; Forsyth and Krizek, 2009; Goodman et al., 2013; Ogilvie et al., 2011). The promotion of cycling through investments may include the construction of new facilities, improvements to existing bicycle facilities and also advertising and educational campaigns. Parkin and Koorey (2012) argue that to support potential success, strategies and design should address whole networks or neighbourhoods rather than individual delinked elements of the infrastructure.

Hills (1996) – extending the work presented by SACTRA (1994) - defines trips that would not have been made prior to a given improvement as induced trips. Narrowing this down to address cycling, *induced cycling* can be defined as cycling trips that would not previously have been made by bicycle. Hills (1996) further distinguishes between rather short-term situations where the destination of trips made remains the same as before the improvement, and more long-term situations where new destinations are incorporated by the road users (changing jobs, location of shopping, etc.). The latter is also called second order effects (see also Ogilvie et al., 2011).

The studies addressed by SACTRA (1994) and Hills (1996) focus on car-based infrastructure where the main aim is often to reduce congestion. The investment in bicycle infrastructure targets several additional environmental and health benefit objectives. Accordingly, these goals can only be achieved when induced cycling appears, i.e. increased cycling frequency of already active bicyclists or when citizens change transport mode. If all new bicyclists on an infrastructure are transferred from other routes and no behavioural shift of present bicyclists takes place, no effects on emission, traffic congestion or public health can be anticipated (Ogilvie et al., 2011; Goodman et al., 2013; Krizek et al., 2009). As a consequence, a simple assessment of the change in cycle loads, for instance by means of automatic counting stations, will be insufficient; it needs to be qualified. One source of information for such qualification is questionnaire surveys (Krizek et al., 2009).

One reason to improve bicycle infrastructure that is often neglected during assessment is the well-being of the bicyclists. Improving the well-being of bicyclists may serve as an advert that targets non-cyclists, which may lead to a mode shift through social feedback (Ogilvie et al., 2011). In regions with a high mode share of bicycle transport, achieving a further increase in mode share can be challenging. In such regions, planning to enhance the well-being of bicyclists may be conducted in parallel with planning to increase the mode share of bicycles as this may be a goal in itself. This study is limited to addresses measures of cyclists well-being in relation to the improvements of the studied infrastructures (mainly surfacing and streetlight).

For many larger investments in bicycle infrastructure, quantification of the effects is a specific focus. In a Danish context, 'Odense Cykelby' (Troelsen et al., 2004) was a comprehensive improvement project for the entire city of Odense, the third largest city in Denmark. The effects were evaluated for the entire city by a cross sectional study based on telephone interviews. The most significant result was that the cycle mode share increased by 20% as a consequence of the improvements.

In the United Kingdom, an independent multidisciplinary collaboration called iConnect (2014) aimed to establish a theoretical basis for assessing the societal effect of improvement projects to build or improve walking and cycling routes at 79 locations around the country framed by the national project Connect2 (Ogilvie et al., 2011). The assessment, which had a special focus on health benefits, was conducted as a cohort research design, which recruited citizens living closer than 5 km to the improvement sites. In the evaluation of three sites reported by Goodman et al. (2013), respondents filled in a questionnaire before the improvements, and again after one and two years. One of the many conclusions reached was the level of use of new infrastructure was higher after two years than the first year after construction, and that the main predictor of using the new facilities was respondents' prior level of walking and cycling activity (Goodman et al., 2013).

Similar studies of effects of infrastructure improvements have been conducted both with a focus on the inhabitants of the case area (Keall et al., 2015) and by directly addressing the cyclists en route, the users of the improved or added infrastructure (Kesten et al., 2015). The present study is an example of the latter.

The present study attempts to identify modal share changes after bicycle infrastructure improvements, although it has several important differences compared to previous studies. Firstly, we investigate behaviour in a society with an already high cycling modal share. Consequently, we would expect the short-term modal shift to be smaller. Furthermore, in the studied region, commuting is the main reason for cycling. In addition, the weather conditions were included as explanatory variables. In accordance with previous studies (Brandenburg et al., 2007; Meng et al., 2016; Miranda-Moreno and Nosal, 2011; Nielsen et al., 2016; Thomas et al., 2013; Thomas et al., 2009) weather conditions include daily measures of sun hours, precipitation and average temperatures. We did not include wind since it was expected to have contradictory influence (contrary and tailing winds will have opposite effect). Thomas et al. (2013) and Thomas et al. (2009) include wind velocity. Not as a single factor, but as part of an aggregated indicator of the weather. Like Miranda-Moreno and Nosal (2011) the present study includes time of year, week and day as explaining factor and the weekday/weekend ratio as in indication of commute vs recreational cycling. This study further adds a ratio of rush hour/non-rush hour for the same purpose. Correcting for climate and temporal variation may, therefore, be essential for analysing the effect of improved infrastructure. Finally, bicyclists' user-experience and satisfaction are also investigated.

The study is based on an assessment of changes in bicycle volumes as well as bicyclists' behaviour/experiences following two bicycle infrastructure improvements in Copenhagen, Denmark. The two case projects addressed are examples of projects which aim to create or improve infrastructures, i.e. develop connections of (existing) bicycle facilities across a larger region. One of the two – the "Albertslund Route" - is an example of an 18 km radial route which is part of the scheme 'Cycle highways of Greater Copenhagen' (Cycle Super Highways, 2013). The other – "Vestvolden" – is a 15 km tangential route on the periphery of the metropolis area of Copenhagen, which was upgraded as part of the 'Copenhagen Fortification Project (2013) (See Fig. 1).

The assessment is based on data from counting stations over a period of 35 months before and after the infrastructure improvements and questionnaires to bicyclists before and one and two years after.

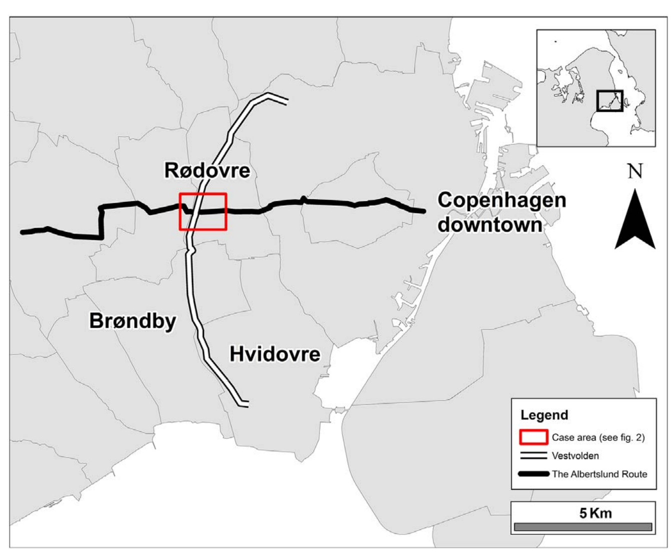

Fig. 1. Location of Vestvolden and the Albertslund Route in the Copenhagen region.

Consequently, we focus on the short-term effects. Second order effects assessed by social modelling, advertising or similar feedback loop effects as suggested by Ogilvie et al. (2011) are not part of the study. The only link to second order effects is through analysing the well-being of bicyclists, which can be argued to lead to second order effects in the longer run.

In summary, the research questions of the study are:

1. What is the increase in bicycle flows as a consequence of improvements in bicycle infrastructure, what changes in the composition of demand can be identified, and what other factors influence the number of bicyclists?
2. How large a proportion of the increase in bicycle volume can be attributed to induced cycling?
3. What effect do the improvements have on users' experience and bicyclists' satisfaction?

2. Case description and background

Copenhagen is a region with a relatively high mode share of bicycles: 35% of all trips performed by inhabitants of the Municipality of Copenhagen (at the core of the region) are made by bicycle (Jensen, 2013; Buehler and Pucher, 2012). In the suburban municipalities immediately surrounding the site of investigation, the share of bicyclists is lower, but it is still in line with the rest of Denmark, with a mode share of 18% (Buehler and Pucher, 2012). According to the Danish Road Directorate (2013), cycling's share of all types of trips in the municipality of Hvidovre is 23%, while it is 19% in Rødovre and 14% in Brøndby (see Fig. 1). Numbers are update annually. Those referred align with the period of the study.

The infrastructure improvements analyzed in this paper consist of two routes – a cycle greenway: Vestvolden and a cycle highway: the Albertslund Route. The route along Vestvolden is part of the Copenhagen Fortification Project (2013) (see Fig. 1). Vestvolden is a part of the former fortification of Copenhagen, which was built from 1858 to 1918, and forms a 15 km earth defence rampart around Copenhagen. Today it appears as an avenue of trees, which is located 15–20 km from the centre of the metropolis area, and serves recreational purposes (apart from commuting). The improvements to the route include new surface and light conditions along a substantial part of the route. Furthermore, but not in focus here, the project also included a number of trial- and playgrounds intended for bicyclists (Schipperijn et al., 2015), roller skate tracks, and a range of information activities including the establishment of an information centre, the installation of signs, and the publication of leaflets, audio guides, etc. to attract leisure bicyclists. The improved route was opened to the public in October 2011.

The other infrastructure studied – the Albertslund Route – is an almost 18 km route, which runs from the western edge of the metropolis area to the city centre. The improved route was opened in April 2012 as the first of the system of ‘Cycle highways of Greater Copenhagen’ (Cycle Super Highways, 2013), which is a network of 22 municipalities in the Copenhagen region and the regional planning authority of Copenhagen. The overall goal of the network is to enhance the conditions for cycle commuters through improved surfacing, connectivity, signage, lighting, etc. The plan is to construct a total of 28 routes (totalling 500 km), most of which extend from the periphery to the centre of the region. Most stretches represent improvements to existing routes and facilities, while only few are newly constructed infrastructure.[1]

As a cycle highway, the Albertslund Route is regarded as a commuter route (Cycle Super Highways, 2013), whereas Vestvolden has a more mixed use pattern. Prior to the upgrade Vestvolden had been regarded to be a green recreational area/route (see e.g. Copenhagen Fortification Project, 2013) but the upgrade allows it to also serve as a link across existing radial commute routes connecting central Copenhagen with its suburbs (Tetraplan, 2009). According to the present study the number of bicyclists on the Albertslund Route is 5–6 times higher than on Vestvolden.

3. Method

The present survey comprised two main sources of information: Automatic bicycle counters in operation during the entire project period of 35 months and three questionnaire campaigns.

3.1. Automatic counters

For the present investigation, two automatic counters (Eco-Combo GSM Pedestrian + Cycle (Eco Counter, 2013)) were installed in October 2010 (see Fig. 2): one located on a 50 m stretch where the two routes cross/overlap and one just 100 m to the north. The (almost) colocation of the two counters enables comparison of the measurements without controlling for differences in the surrounding urban structures. The hourly volume of bicyclists was calibrated by visual/manual counts to determine the actual number of bicyclists. It was estimated that each registration by a station corresponds to 1.23 bicyclists ($n = 20$, (Brandenburg et al., 2007) $r = 94\%$), the underestimation is believed to be due to the inability of the equipment to distinguish individual cyclists when several pass at the same time. The northern counting station (Station 1, see Fig. 2) only counts users on the Vestvolden route, while the southern (Station 2) counts users on both routes. Accordingly, the volume on the Albertslund Route is estimated as the difference between the two (the counts from Station 2 minus the counts from Station 1). See Fig. 3.

The data from the counting stations was analyzed by linear regression where the recorded count for a single hour was modelled as dependent on the time of year/week/day, the weather and a constant indicating the presence of one station instead of the other (of the two included). The reason to include these dependent variables is to correct the assessment of interest (before or after the improvement) for noise which may be correlated with it. This can be used to predict the number of bicycles given a certain level of the parameters, e.g. for conditions in an average month of May, or an average day of the year. Here we have chosen the latter. In other words the predictions represents the expected, average count for an hour, everything else set even to an average situation. The details of the regression – including a full list of included explaining variables - analysis can be found in Appendix A.

3.2. Questionnaire survey

A web-based questionnaire survey was carried out in May 2011, 2012 and 2013. Respondents were recruited by handing out flyers at the crossing point of the two routes included in the study (coinciding with Station 2 in Fig. 2) and the control site (see Fig. 2). The 2011 campaign was part of a comprehensive assessment of bicyclists' behaviour in Copenhagen (Bikeability, 2014[2]). For the repetitions in 2012 and 2013, a few questions were added relating to bicyclists' change in transport behaviour (self-assessed) and experienced change in the quality and comfort of the routes. Further, respondents at Station 2 (see Fig. 2) were asked whether they had come via the Albertslund Route or Vestvolden. All flyers were handed out between 7:00 and 19:00 on weekdays to catch commuter cyclists rather than leisure cyclists. A total of 694 and 633 responses were obtained at the study site and the

[1] A 50 min video of the entire route from central Copenhagen to the periphery can be seen on Youtube (2013). The location of the present investigation (counting stations and venue for handing out flyers) is passed at 25:30.

[2] Other results of this survey are presented in Vedel et al. (2016).

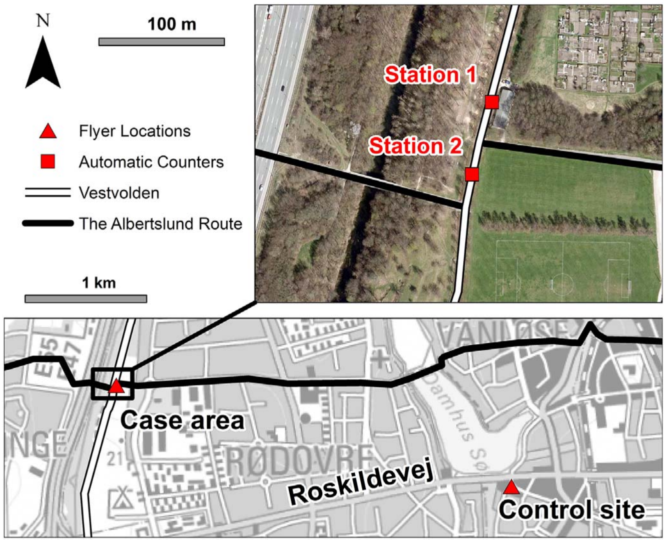

Fig. 2. The location of the two counting stations involved are marked as squares on the upper map (Station 1 and 2), and - on the lower map - the two locations where flyers for recruitment to the web-based questionnaire survey were handed out are marked by triangles. The control location on Roskildevej can be seen on the right.

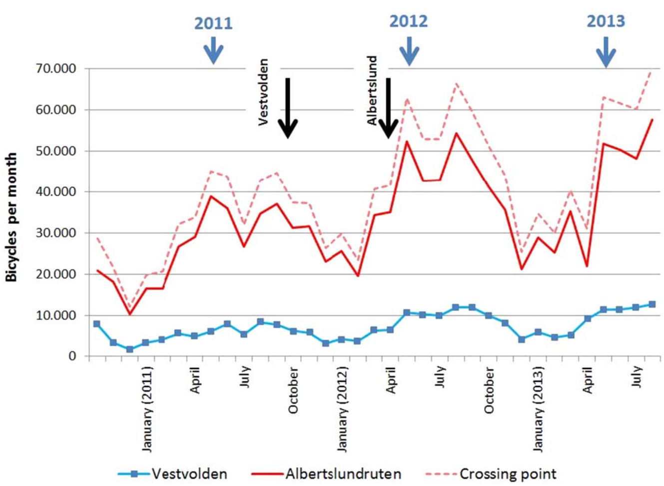

Fig. 3. Calibrated bicyclist loads on the Albertslund Route/Vestvolden recorded by automatic counting stations, relative to the improvements (time of improvement shown as black arrows). Further, points in time (2011 – 2013) where flyers were handed out for the questionnaire survey are marked as blue arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

control site respectively.

To assess whether respondents had changed their transport mode in the previous two years, two questions from the questionnaire were combined: a) do you use the route more or less than one or two years ago (i.e. before the infrastructure improvements depending on the timing of the questionnaire campaign), and; b) if you use the route less then why? The reasons given for changing transport behaviour were; a) modal shift from other means of transport; b) relocation from other routes; c) increased cycling frequency along the assessed route, and; d) the baseline trips performed by bicyclist already before the improvements (see Table 1).

4. Results

4.1. Change and predictors of bicycle flows for 35 months

4.1.1. Overall model

The regression results are shown in Appendix B. The Albertslund Route is used as the reference so that the effects on Vestvolden are additional to the main effects. The regression shows that we are able to explain about 62% of the variation with the included parameters. We see that weather variables, seasonal variables, variation over day/week, and the opening of the two routes have an effect and also that the interaction terms between these are significant. In the following, we look at each of these.

4.1.2. Effects of weather and time of year/week/day

Indicators of weather – daily hours of sunshine and precipitation - turned out to be significant explanatory variables for the number of bicyclists per hour on the assessed routes. As expected, the number of bicyclists rose with more sunshine hours, whereas increased precipitation reduced the volume of bicyclists. Temperature was omitted due to high correlation with day-length. The length of the day – as an indicator of season – was significant too, showing a higher level of use in the summer than during the winter. A significant and positive effect was recorded for the rush-hour and during the hours of daylight. Finally, the number of bicyclists was significantly higher during weekdays than at the weekend.

4.1.3. Predicted effects of improvements

Table 2 shows that the first infrastructure improvement had a significant effect, but the second improvement had no additional effect. However, this depends heavily on the time of day and on which of the two routes is considered. Consequently, Table 3 shows the predicted effects for certain times of the day for average measures of the three continuous variables, sun (4.82 h/day), precipitation (1.6 mm/day), and day length (12.36 h/day) for the period of measurement (Oct. 2011 to Aug. 2013).

As seen from Table 2, the opening of the renewed infrastructure along Vestvolden had no immediate effect on the volume of bicycles on Vestvolden itself for any of the assessed periods of day/week. On the Albertslund Route, modest, but significant, increases for all period types were predicted. For instance, the number of bicyclists rose from 126 per hour to 135 during the rush hour in the light period of the day. After opening the renovated track on the Albertslund Route, a significant increase in the number of bicyclists was estimated during the rush hour on Vestvolden – both during the light and the dark period of the day: an increase from 24 to 32 cyclists per hour during the daylight rush hour, whereas the number increased from 14 to 24 for the rush hour during the dark hours of the day. For bicyclists on the Albertslund Route, the

Table 1
Criteria for assessing the origin of the increased number of bicyclists.

Question	Existing users of the cycle highway/greenway		New users of the cycle highway/greenway	
	No change frequency	Increased frequency	Relocated from other routes	Induced cycling
Do you use this route more or less than one or two years ago? If so, why?	• Did not use the route less	• Did not use the route less	• I cycled along … (one out of five routes listed) • I did not use the area	• I used the car or public transport
Relative to one/two years ago, do you cycle…	• The same amount • Less/a lot less	• More/a lot more	• More/a lot more • I did not use the route	• More/a lot more • I did not use the route

Table 2
Prediction of hourly bicycle volumes. Predictions marked in dark grey are significantly different from the previous period (for the same infrastructure), whereas predictions marked in light grey only increase significantly after both improvements compared to the initial situation. White cells hold non-significant changes in predictions or the base period before improvements. For significant effects, the increase is shown in % in brackets. All predictions are significantly different between the two routes.

	Vestvolden		The AlbertslundRoute	
Before improvements	**Bicycles/hour**	**95% confidence intervals. Lower/upper**	**Bicycles/hour**	**95% confidence intervals. Lower/upper**
Weekdays, day light, rush hour	24	18/30	126	122/130
Weekdays, dark, rush hour	14	8/20	89	86/92
Weekdays, day light, non-rush hour	14	9/19	46	43/49
Weekend, day light	11	7/15	34	32/37
After the improvementat Vestvolden (II1)				
Weekdays, day light, rush hour	22	11/34	135 (7%)	129/142
Weekdays, dark, rush hour	15	4/25	98 (10%)	92/104
Weekdays, day light, non-rush hour	12	3/21	53 (15%)	48/58
Weekend, day light	10	3/17	41 (21%)	37/45
After the improvementat the Albertslund Route (II2)				
Weekdays, day light, rush hour	32 (33%)	18/46	203 (61%)	195/210
Weekdays, dark, rush hour	24 (71%)	12/37	154 (73%)	147/160
Weekdays, day light, non-rush hour	12	1/22	70 (52%)	64/75
Weekend, day light	11	2/19	54 (59%)	49/58

Table 3
Proportion of bicyclists according to their previous transport behaviour aggregated for the two routes (which were not significantly different from each other). The differences between years are significant at the 1% level (Fishers exact probability < 0.0001). 88 of the original 442 responses were removed due to incomplete information.

n = 354	Existing users of the bicycle highway/greenway		New users of the bicycle highway/greenway	
%	No change frequency	Increased frequency	Relocated from other routes	Induced cycling
2012	46	1	49	4
2013	30	3	61	6

counts increased from 126 to 203 for the rush hour during the light period of the day, whereas the figure for the dark rush hour increased from 89 to 154. Note the difference in the number of dark vs daylight rush hour counts: for Vestvolden, there is a clear increase in the relative number of bicyclists for the dark rush hour from 14 to 24 (71%) compared to 24–32 (33%) for the daylight rush hour, whereas the proportion for the Albertslund Route shows a modest increase from 89 to 154 (73%) and from 126 to 203 (61%) for the dark and daylight rush hours respectively. This indicates a specific increase in commute cycling during the dark hours of the day at Vestvolden after the infrastructure improvement, which was not observed on the Albertslund Route.

Comparing weekend/weekday and rush hour/non rush hour ratios (as indicators of commute vs. recreation cycling), the two improvements do not have any unambiguous effects on the number of bicyclists on the Albertslund Route. The weekend/weekday ratio rose from 34/46 (74%) in 2011 to 54/70 (77%) after the renewal of both routes (in 2013), which indicates a slight tendency towards increased recreational cycling. The ratio of non-rush hour/rush hour remained the same: 46/126 (35%) in 2011; 70/203 (35%) in 2013. For Vestvolden, the same pattern towards recreational cycling appears, but changes over time were not significant. Overall, Vestvolden displays a slightly higher tendency for recreational cycling, but no significant change over the periods of investigation was observed. In terms of weekend/weekday before improvements, the ratio was 11/14 (79%) on Vestvolden compared to 34/46 (74%) for the Albertslund Route.

4.2. Behaviour changes and user satisfaction from before to 2 years after opening

4.2.1. Changes in frequency and distance cycled

The questionnaires in 2012 and 2013 included stated (self-reported) changes to distances cycled and the frequency of trips from before any of the infrastructure improvements (in 2011) till the respective dates of the survey. Results for both routes showed no significant differences in the number of bicyclists who reported that they cycled further or more frequently compared to the responses of the control sample (Respondents recruited at Roskildevej).

4.2.2. Changes in transport mode

To determine the distribution of changes in bicyclists' transport behaviour in terms of frequency, route and mode, respondents were classified according to the schema found in Table 1. The results are presented in Table 3.

The distribution changes significantly (based on a Fisher exact test) from 2012 to 2013, so that the share of "new bicyclists", which includes both bicyclists who have changed their route and those who have changed mode from another means of transport, are observed. Further, the number of respondents reporting increased frequency has increased. Accordingly, the number of bicyclists who previously would not have made the trip by bicycle, i.e. induced bicycle trips, increased from 4% to 6%.

It was not possible to calculate the potential effect of relocated bicyclists who change their frequency of use at the same time by the method applied.

4.2.3. Changes in satisfaction with route facilities

Respondents were asked to state their impression of the condition of the routes compared with the situation before the improvements.

Table 4
Share of respondents who reported that conditions had improved ('better' or 'much better'), compared to the situation before the improvements. Significance levels refer to pairwise chi-square comparisons between the investigated routes and the control for each year. For location of assessed routes and control, see Fig. 2.

% of respondents (2012/ 2013)	Albertlundruten	Vestvolden	Roskildevej (control route)
Surface condition	78[a]/66[a]	89[a]/82[a]	15/9
Lighting conditions at night	67[a]/63[a]	88[a]/68[a]	6/0
Safety in the traffic	33[a]/27[b]	52[a]/29[b]	8/10
Personal security	32[a]/23[a]	48[a]/18[a]	6/5

[a] Indicates significance at 0.1% level.
[b] Indicates significance at 1% level.

Significant differences were found between the routes and between the two years of assessment. The results are shown in Table 4.

On both Vestvolden and the Albertslund Route, bicyclists express they have experienced a significant improvement in the conditions compared to the control site at Roskildevej. The proportion of respondents who claim that the lighting and surface conditions have improved is generally higher for Vestvolden than for the Albertslund Route, which corresponds well with the fact that the upgrade of the surfacing and lighting on Vestvolden was more comprehensive (from gravel road with no light to a well-lit, paved path along an extended continuous portion of the route) than for the Albertslund Route where the changes were more sporadic. The experienced improvement in safety and security is lower than for lightning and surface conditions. The fact that the evaluation is lower for the Albertslund Route than for Vestvolden is primarily due to the improved lighting conditions. Some respondents from the control route (Roskildevej) express they had experienced an improvement even though no improvement had been made. However, the proportion was significantly lower than for the other sites.

In all cases, there is a tendency that experiences were less positive after two years than after one.

5. Discussion

This study has investigated the effect of bicycle infrastructure improvements in terms of the volume of bicyclists, the effect on transport behaviour – including induced trips - and bicyclists' user experience and satisfaction. This is important for policy and, consequently, it stresses the importance of the accuracy of the measures. In the following, we discuss each of the investigated effects separately.

The discussion, among others, compares the results with previous *ex-ante* and *ex-post* assessments of the effects of the improvements of the present case infrastructure developments.

We are indeed aware of the fact that transport in Denmark, and in particular Copenhagen, in general has a very high share of bicycles and that results of the present study should be seen in that light. The implications for comparability with infrastructure improvements in regions with smaller volumes of cycling is, however, not straightforward. On one side the effects of bike-infrastructure improvements may be expected to be small because so many citizens are already cycling and the relative improvement to the infrastructure small. On the other side improvements might have a better starting point for inducing effects as the wider physical and social setting (the bicycle oriented mobility) already support cycling and can cater for immediate reactions to – more or less local - changes to the infrastructures. Transfer of the findings of the present results to other regions of the World should not take place without further consideration of the role of the contexts.

5.1. Changes in bicycle flows

An investigation of the effect of improved bicycle infrastructure requires corrections to be made to the observed numbers for temporal and climatic variation. Furthermore, the effects must be assessed over an extended period of time after improvements have been completed. The latter is most clearly illustrated by the lack of immediate effects resulting from infrastructure improvements along Vestvolden, which is partly due to longitudinal effects which extend beyond the relatively short period of time (6 month) to the opening of the improved Albertslund Route. An alternative model for the bicycle counts, where the time since opening Vestvolden was applied as a continuous explanatory variable (months since opening), but where the time after the improvement of the Albertslund Route was kept as a dummy variable, supported the hypothesis. The analysis can be interpreted as indicating that the improvements to the Albertslund Route actually had an additional positive effect on the level of use of Vestvolden at the site of investigation. However, we cannot directly infer this causality. Over a longer period of time – two years after – the most significant increase in the number of bicyclists on Vestvolden (71%) was during the rush-hour on weekdays during the dark hours of the day. This change can, thus, be seen as a direct consequence of the provision of lighting along the path as previously no lighting had been provided.

The assessment of the effect of the improvements on the Albertslund Route, performed by COWI (2012) by means of counting stations, recorded a modest rise of 6% during weekdays and a drop of 37% on weekends. The results seem to be questionable and are considered to be a result of the fact that counts were made during very short one-week periods and that no attempt was made to introduce additional controls (for e.g. weather, season, etc.). In fact, the decrease on weekends is assumed to be due to rainy weather during the counting campaign post-improvement (COWI, 2012). Quantification by means of automatic counting stations requires measurement over extended periods of time and control for weather conditions and season. To control for weather and seasonal effects, a measurement period of a minimum of two years after improvements have been implemented is recommended, or alternatively, the application of parameter estimates from the present study (or similar) in future counting campaigns.

On Vestvolden, an *ex-ante* model-based assessment made by Tetraplan (2009) before the project was initiated anticipated a decrease in cycling along the route over an extended period of time due to a pull effect from improvements made to surrounding and competing infrastructure (including the Albertslund Route). This is not supported by the present study, which documents a continued increase in cycling over the two-year recording period (since the improvement to Vestvolden). This seems to be the consequence of a prolonged effect of the improvement itself and an additive effect (rather than the opposite) of the enhancement to the Albertslund Route. The contrast with the *ex-ante* result highlights the need to further develop modelling capacity for cycling so that the modelling results become more realistic and reliable.

5.2. Contribution from induced cycling

We estimate the share of induced cycling trips to be 4% in 2012 and 6% 2013. This may seem rather low given the objectives of improved cycling infrastructure. One main reason for these modest estimates may be that we are investigating cases in a region where the general mode share of bicycles is relatively high. However, it has not been possible to identify comparable assessments from regions with a lower bicycle mode share to support this hypothesis. Based on bicyclists' self-reported information, van Goeverden et al. (2015) report modal shifts from car to bicycle as a consequence of realised bicycle infrastructure improvements of between 2% and 3% and 2% and 5% for three Dutch and Danish cases respectively were reported. In Sweden (which, in general, is considered to be a nation with a high bicycle mode share), a study based on a variety of choice experiments predicted modal shifts to bicycle transport of between 3.9% (raising from 51 to 54.9%) and 10.3% (raising from 51 to 61.3%) it was predicted, depending on the magnitude of the improvements (Björklund and Isacsson, 2013).

Obtaining estimates of induced cycling is challenging as it requires identification of, e.g. reallocation of trips. The approach applied here is based on respondents' self-assessed change in behaviour, which naturally only counts the newcomers and not the ones who leave. To quantify significant effects of improvements to a specific infrastructure in a way that caters for citizens that have stopped cycling along it or changed transport mode away from bicycling, would be to conduct a household survey, which potentially requires a substantial number of respondents (see, e.g. Keall et al., 2015; Goodman et al., 2013; Ogilvie et al., 2011).

5.3. Effects on bicyclists' experiences and motives for route choice

The improvements to the infrastructure have a significant effect on bicyclists' experiences of the route characteristics. Bicyclists experienced a significant improvement in the surface and lighting conditions. Similarly, a significant improvement in perceived (traffic) safety and personal security was recorded. The effects were particularly pronounced at Vestvolden, where good surfacing and streetlights were introduced; both of which had not been present previously. Generally, it seems that respondents' impressions become less positive as time goes by. This may be due to either fading memory. The findings are strongly supported by a comparison with the responses obtained from bicyclists on the control site at Roskildevej. While measures of cyclists' satisfaction can be a specific objective as in this case, it may also lead to second order effects in terms of people changing behaviour in the long run. However, this was not tested in the current context as it would require the application of completely different methods.

The level of satisfaction - compared to the control route – was observed to be more significant after one year than after two. While it is not be supported by the available data, it can be hypothesised that this may be due to respondents' fading memory of the past.

6. Conclusion

The study shows that improvements to the cycle greenway, Vestvolden, and the cycle highway, Albertslund Route, in Copenhagen led to a gradual increase in the number of bicyclists using them including citizens who have changed mode of transportation in favor of the bicycle. The hourly volume of bicyclists, which was monitored continuously over 35 months, was significantly influenced by the weather and the time of day, week and year. Controlling for such factors and measuring for an extended period of at least 1–2 years after opening is necessary to obtain valid and reliable estimates of changes in the volume of bicyclists. It can be expected – as in the present study – that the effects of infrastructural changes will continue for a period of time beyond the initial effects seen during the first few years after the improvements.

Most of the increase in the flow of bicyclists along the two routes can be attributed to bicyclists switching from alternative routes to the improved routes when they open. Only a modest share (4–6%) of the bicyclists on the renewed routes switched to cycling from other transport modes. Therefore, the effect on the three main pro-cycling policy outcomes discussed in the introduction, environmental gains, reduced traffic congestion, and enhanced public health, is likewise modest.

Cyclists on the improved routes express significantly higher satisfaction with surface and lighting conditions than before the improvements. In addition, perceived traffic safety and personal security was significantly better. This can be expected to lead to bicyclists maintaining or even increasing their use of cycling as a mode of transport. Furthermore, a high level of satisfaction among existing bicyclists may serve as a good advert for the remainder of the population, potentially persuading some to switch to using a bicycle instead of other means of transport.

A final, concluding remark is that the effects of improving bicycle infrastructure cannot be assessed entirely by volumes of bicycles before/after improvements as in the above-mentioned *ex-ante* assessments. To obtain a more complete picture, an assessment of the proportion of induced cycle trips and bicyclists' user experience and satisfaction should be included as in the present study.

A. Specification of statistical model

To identify reasons for changes in bicyclist counts at a counting station, a linear regression of the hourly number of bicyclists, N, was estimated:

$$N_t = \alpha + \beta I_t + \gamma S_t + \delta L_t + \varepsilon_t$$

here α is a constant, β a vector of parameters for the variables describing the presence of an infrastructure improvement I, γ and δ are parameters for variables controlling for seasonal and temporal differences (S) and locations (L), and ε is an error term, assumed *i.i.d.* All variables are dependent on the observed time t. The infrastructure improvement variables (I) are defined based on the presence; (a) before any of the improvements; b) after improvement to Vestvolden, but before the Albertslund Route, and; c) after improvement to the Albertslund Route. The seasonal and temporal differences were addressed by weather (daily precipitation, hours of sunshine, and temperature), time of the year (represented by day length), time of the day (rush hour (7–9 AM and 4–6 PM)/non-rush hour/night), week days/weekends, day light/dark (a 'day light hour' is the hours between sunrise/set plus the twilight hours (i.e. the periods during which the sun is $< 6^0$ below the horizon)). To distinguish the two routes, a location dummy for the Vestvolden location was included. Furthermore, interaction between these variables was included, in particular the location.

B. Parameter estimates

Variable	Estimate	Error	*t*-Value	Pr > |t|
General				
Intercept	− 5.13822	0.80664	− 6.37	< 0.0001
Sun hours (daily hours 0.00–16.00)	0.72308	0.03552	20.36	< 0.0001
Day length (hours 6.95–17.62)	0.17167	0.04646	3.70	0.0002
Precipitation (daily mm - 0.00–72.60)	− 0.26713	0.03293	− 8.11	< 0.0001
Week and day variation				
Weekday (dummy)	11.90666	0.6903	17.25	< 0.0001
Rush hour (dummy)	76.73544	0.97476	78.72	< 0.0001
Day light (dummy)	34.00933	0.62917	54.05	< 0.0001
Infrastructure improvements				
II1, Vestvolden (dummy)	3.15462	1.11195	2.84	0.0046
II2, Albertslund Route (dummy)	0.94869	0.88876	1.07	0.2858
Week and day variation interacted with infrastructure improvement				
Day light x II1	3.60133	1.06995	3.37	0.0008
Weekday x II1	− 0.03066	1.18642	− 0.03	0.9794
Rush hour x II1	5.74644	1.68442	3.41	0.0006
Day light x II2	11.83613	0.82006	14.43	< 0.0001
Weekday vs x II2	4.06294	0.90007	4.51	< 0.0001
Rush hour x II2	50.81255	1.27416	39.88	< 0.0001

Additional effects when counting on Vestvolden				
General				
Counts on Vestvolden (VV, Station 1), VV (dummy)	0.92863	0.94988	0.98	0.3283
Week and day variation				
VV x weekday	− 10.50521	0.97414	− 10.78	< 0.0001
VV x rush hour	− 66.04317	1.37795	− 47.93	< 0.0001
VV x day light	− 25.69583	0.88063	− 29.18	< 0.0001
Infrastructure improvements				
VV x II1	− 2.26835	1.56746	− 1.45	0.1479
VV x II2	− 0.0526	1.2541	− 0.04	0.9665
Week and day variation interacted with infrastructure improvements				
VV x weekday x II1	− 6.18028	2.38195	− 2.59	0.0095
VV x weekday x II1	0.73278	1.67685	0.44	0.6621
VV x day light x II1	− 4.18992	1.51035	− 2.77	0.0055
VV x rush hour x II2	− 41.75273	1.80192	− 23.17	< 0.0001
VV x weekday x II2	− 3.62956	1.27115	− 2.86	0.0043
VV x day light x II2	− 9.56539	1.15946	− 8.25	< 0.0001

Parameter estimates of a linear regression of number of bicyclist per hour. N = 50954, 21 degrees of freedom, (Brandenburg et al., 2007) R = 0.62. Base line: Counts on the Albertslund Route (Station 2) before improvements, on weekends, at night (21:00 to 6:00), during dark hours of the day.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: https://doi.org/10.1016/j.jtrangeo.2017.09.011. These data include the Google map of the most important areas described in this article.

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