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Do highway widenings reduce congestion?

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Abstract

Highway construction occurs nowadays mainly through widening of existing roads rather than building new roads. This article documents that highway widenings considerably reduce congestion in the short run, defined here as 6 years. Using longitudinal micro-data from highway detector loops in the Netherlands, we find substantial travel time savings. These savings occur despite strong increases in traffic flow. The welfare benefits in the short run already cover 40% of the widenings' investment costs. Our article contributes to an explanation why countries invest in roadworks even when the fundamental law of congestion predicts that travel savings disappear in the long run.

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JEL classifications: R3, R33, R4, R42, H4
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1. Introduction

Highway construction has occurred over the last decades largely through widenings—adding new lanes to existing roadways—rather than through construction of new greenfield highways in developed countries. In the Netherlands, for instance, very few new greenfield highways have been built after 1990, whereas highway lane kilometres have increased substantially, by about 25%. Furthermore, the construction of highway widenings has been planned to continue at the same rate as in previous decades, whereas there are very few new highways planned. Various other countries show a similar pattern of slowing down of new highway construction (e.g. USA, see Winston and Langer (2006), but also West European countries such as Germany, France, Italy and UK, see European Commission, 2018).

There exists an important body of literature on the effects of greenfield highways, but much fewer papers study widenings. This is unfortunate because the size, timing and scope of the effects differ substantially between these two types of roadworks. The greenfield highways offer car travellers alternative routes, improving the road system's coverage. The travel time savings may be large but also are varied as travel time reductions are not restricted to the congested hours only. Further, alternative routes may induce substantial changes in spatial structure—in terms of population and employment. These changes take time, particularly when it involves the construction of new buildings, so that the overall effects of greenfield highways reveal themselves in the long run only.[1]

In contrast, widenings typically take place on congested highway segments. The direct (welfare) effect of this increase in road capacity arises due to local reductions in travel time, that is, on the widened segment self, during congested hours. This further induces adjustments in travel demand within the day (e.g. from nonpeak to peak), over space (i.e. from adjacent highways to treated highways) and in overall travel demand.[2] This makes it plausible that the major part of the effects of widenings can be observed on a much shorter term than is the case with greenfield highways. As a result, in the case of widenings, the short-run effects might be especially important. While there is evidence that the travel time reductions disappear in the long run due to an induced increase in travel demand (Hsu and Zhang, 2014; Garcia-Lopez et al., 2021), the welfare benefits may still be substantial during the transition to this new long-run equilibrium. Another important reason why to focus on widenings separately from other road extensions is that the construction costs of widenings are much lower than those of greenfield highways.[3]

In the current article, we aim to examine the short-run welfare effects of highway widenings, which are ignored in the literature. We examine these effects for the Netherlands, where widenings mainly occurred on highways between cities. We include the effects on congestion (travel time) and travel demand (traffic flow) up to 6 years after a widening. We study how these effects vary by year within this time interval. Furthermore, we study also the variation in the effects within the day, which is relevant because of trip rescheduling (Arnott et al., 1990, 1993; Small et al., 2005), as well as over space (i.e. within a certain distance of the widening). Our (welfare) estimates complement studies that focus on the widenings in the long run (Hsu and Zhang, 2014; Garcia-Lopez et al., 2021) and on greenfield highways (Duranton and Turner, 2011; Couture et al., 2018) and therefore help getting a more complete picture to gauge the welfare implications of highways investments.

A widening increases the number of lane kilometres for a certain area. Our identification strategy exploits the variation over time and space in the number of lane kilometres induced by widenings. We make use of information from individual induction loop traffic detectors for the Dutch highway network, which allows us to estimate the effects for several levels of aggregation.[4] Our focus is on a region defined by the geographical area within 20 km of a widening. Regions are therefore quite sizeable (about 630 km^2).[5]

1 In addition to changes in spatial structure, there are other reasons why traffic flows do not immediately fully adjust given reductions in travel time. For example, commuters do not immediately move to another job when commuting time decreases, because it takes time to find alternative employment, whereas it also takes time for wages to adjust (Van Ommeren et al., 1999; Mulalic et al., 2014). In addition, the presence of substantial residential transaction costs is an important reason of why households do not move residence immediately after facing changes in their commuting time (Larsen et al., 2008). Slow adjustments of traffic flow are also consistent with a body of literature that shows that the fuel price elasticity of car travel demand is much smaller in the short run than in the long run, see for example, Brons et al. (2008) for a review.

2 The effects of widenings therefore depend on whether treated highways are substitutes or complementary to adjacent highways. For example, parallel roads tend to be substitutes, but the roads may also feed into each other. Usually, except when Braess paradox exists, average travel time within the highway network will not increase, because of widenings.

3 Estimates for the Netherlands indicate that the cost of a lane kilometre of a widening is roughly one-fourth of the cost of a greenfield extension.

4 In the literature, it is standard to use information for administrative regions. Using more fine-grained information is particularly beneficial for identification in small, high-density, countries such as the Netherlands.

5 Regions are one-fifth of the median US county size, but with much higher levels of population and employment density.

Additionally, we examine the effect of widenings locally, that is, at the level of the highway segment, our smallest unit of analysis (a segment has an average length of 12 km). Analysis at this level is useful as it allows us to examine spatial variation in the effects of widenings within regions, including whether highways are substitutes or complements to each other. Importantly, analysis at this level is politically relevant, as the local effects of widenings are very pronounced and therefore visible.

We take several steps to account for endogeneity issues. To control for unobserved time-invariant heterogeneity, we use location fixed effects. This does not control for time-varying heterogeneity which may be problematic when time-varying location characteristics are correlated to highway widenings.[6] Furthermore, we focus solely on segments, respectively, regions where road capacity increased during the study period.[7] This relaxes the identifying assumption for causal inference, as it only requires that, conditional on the widening, the exact timing of the widening is random. To justify this assumption, we discuss the Dutch transportation investment planning process and explain that it involves many phases of consulting with several layers of government and local residents which lead to unpredictable—and therefore arguably random—adjustments to the exact timing of the widening. For example, only about 10% of the new lanes were opened in the planned year.

We focus on the dynamic effects of widenings, that is, we employ an event study, to estimate the short-run effects we are interested in. Consequently, our identification strategy is based on the idea that widenings cause large *discrete jumps* in travel time as well as flow. The threat to identification from discontinuous confounding factors is then limited, because widenings vary considerably in opening year and geographical location. It is highly unlikely that all widenings were in the same way affected by the same confounding variable.

Our identification strategy is based on a discrete jump in kilometre lanes in a region, but ignores that the 'treatment dose'—that is, the size of the increase in number of kilometres—may be endogenous. We address the possible endogeneity of the 'dose' by using an instrumental variable (IV) approach. We use as instrument an indicator capturing the number of widenings in the area surrounding a detector since the start of the study period. The value of the instrument is therefore detector and year specific. Given detector fixed effects, this instrument essentially captures whether in a specific year there was at least one widening. By construction, the instrument is not related to the 'treatment dose', as it does not depend on the number of kilometres lane added. So, it takes the same value whether a widening involves adding one or two lanes of a specific kilometre length, or whether a widening involves adding few or many kilometres.

Our methodology may be contrasted with estimation strategies that do not rely on the discrete change in lane kilometres of highways, but on historic IVs, see for example, Baum-Snow (2007), Duranton and Turner (2011), Levkovich et al. (2020) and, recently, Garcia-Lopez et al. (2021). These methodologies have several advantages, as they do not build on the conditional independence assumption only. They may be the preferred approach if the historic instrument can be assumed to be exogenous (which is not entirely unproblematic), and also sufficiently strong. In particular, the latter is an issue in our context, because the instruments in question usually have good predictive power to predict

6 Reverse causality is potentially an important threat to identification. For example, highways might be widened at locations where congestion is expected to increase. We address this issue by focusing on *sudden* changes.

7 We demonstrate however that our estimates are robust with respect to this selection.

the *level* of highway capacity, but have more difficulty predicting short-run *changes* in highway capacity (Garcia-Lopez et al., 2021). So, these instruments are particularly appropriate for studies with many observations of large distinct geographical areas that focus on the long-run effects. In contrast, our study focuses on short-run effect of widenings for a smaller country using observations of overlapping geographical areas making historical instruments less appropriate.

We first document that widenings are far from random and occur on highway segments that are highly congested particularly during peak hours. Widenings substantially increase road capacity: a widening increases the number of lanes of the widened segment by about 50%. This is also true at the regional level (in our study, regions have a 20-km radius): road capacity of regions that receive at least one widening increases, on average, by 10%.

We find considerable travel time reductions and travel demand increases after widenings on treated road segments, particularly during peak hours. The majority of these changes take place almost immediately after the widening. These results are important as they explain why widenings are politically attractive. We also find substantial reductions in travel time (with an elasticity of -0.7) and increases in travel demand (with an elasticity of 0.5) at the regional level. These effects remain during at least 6 years after a widening.

To examine the welfare effects of widenings, we include four important components of welfare: (i) the time *losses* because of road construction just before the widening, (ii) the gains because of reduced travel times after a widening, (iii) the gains because of rescheduling and (iv) construction and maintenance costs of widenings. Our main conclusion is that 6 years after the widening, the accumulated welfare gains are substantial and cover 40% of the overall investment costs.

Finally, we investigate to what extent widenings cause local changes in economic activity (i.e. employment) and spatial structure (i.e. real estate). We provide evidence that highway widenings induce moderate redistributions of employment and commercial floor space within a range of 10 km, but the effects on population are too small to detect.

The structure of the article is as follows. Section 2 deals with the literature. Section 3 describes the Dutch institutional setting of highway investments, which is essential for our identification strategy, and discusses the data on widenings. Section 4 examines the effect of widenings on travel outcomes, dealing consecutively with the traffic data, the empirical model and identification, and the results. Section 5 discusses the welfare effects and policy implications of the effects of widenings on congestion. Section 6 goes into the effects of widenings on local economic activity and spatial structure. Section 7 concludes.

2. Literature

Our article is connected to several streams of literature. The first one examines how urban traffic outcomes, such as vehicle kilometres travelled, travel flow, speed and congestion are *in the long run* affected by increases in road supply. The seminal paper by Duranton and Turner (2011) finds support for the 'fundamental law of congestion' introduced by Downs (1962): they document a unity elasticity of kilometres travelled in US metropolitan regions to their road infrastructure supply between 1980 and 2000. Hymel (2019) confirms this result on more recent data. Couture et al. (2018) support these findings by reporting a low (0.09) long-run elasticity of traffic speed to road supply for the USA. Hsu and Zhang (2014) and Garcia-Lopez et al. (2021) demonstrate that long-run elasticity of vehicle kilometres for Japan, respectively, Europe is around one with higher estimates for greenfield road construction.

Our article adds to this discussion by documenting for the Netherlands short-run dynamic effects after increases in road supply. We find that 6 years after the widening, the elasticity of travel flow with respect to road supply is about 0.50 (the difference from unit elasticity implied by the fundamental law is statistically significant). The elasticity of travel time with respect to road supply is then about −0.70.

Our study also indirectly relates to a growing literature studying the effects of changes in transport infrastructure on broader travel demand. Gu et al. (2021) and Yang et al. (2018) report increases in speed on Chinese highways following subway line opening adjacent to highways. Gu et al. (2017) document a decrease in travel frequency following the introduction of driving restrictions. Gendron-Carrier et al. (2022), Chen and Whalley (2012) and Davis (2008) report a positive influence of urban transit rail and driving restrictions on air quality. Anderson (2014), Adler and van Ommeren (2016) and Bauernschuster et al. (2017) document increases in car travel time during public transit strikes. Kim (2022) has recently examined the effect of road works aimed at improving the quality of highways in California, USA. He finds an immediate, but temporary effect on speed, which disappears after 1 year. In contrast, traffic flow responds slower.

Another relevant body of literature deals with welfare benefits of transportation improvements (Gibbons and Machin, 2005; Duranton and Turner, 2012; Ossokina and Verweij, 2015; Teulings et al., 2018; Tsivanidis, 2022). By focusing on widenings and employing rich data on car travel time and flow, we are able to estimate the effects of widenings on travel demand and time savings, which are essential ingredients of a welfare analysis. We show that the benefits of the widenings in the first 6 years cover around 40% of the investment costs.

Finally, our article is connected to studies that examine the impact of highways on urban development, and in particular the relocation of population and employment. Baum-Snow (2007, 2010) shows for the USA in 1950–1990 that additional highways passing through central cities led to suburbanisation of population and employment. Garcia-López et al. (2016) report that these effects have become smaller over the last decennia in Europe, likely because of the presence of a well-developed highway network. Levkovich et al. (2020) demonstrate that zoning policies influence how new highways affect population relocation in the Netherlands. Duranton and Turner (2012) show for the USA that new highways caused increases in employment and population in metropolitan areas in 1980–2000. Moeller and Zierer (2018) report substantial effects of new highways on employment in German regions. Baum-Snow et al. (2020) show for China that highways negatively affect hinterland population growth. We complement these studies by focusing on the short-run effects of widenings at a detailed spatial level and find mainly redistribution effects.

3. Background, data and sample

3.1. Highway investment, planning and functioning in the Netherlands

The Netherlands has a high population density and a very developed and dense highway network (World Economic Forum, 2015). About 1% of gross domestic product is spent on highway investment, mainly through widenings and maintenance (Ministry of Infrastructure and Water Management, 2018). Figure 1 shows the highway length and lane

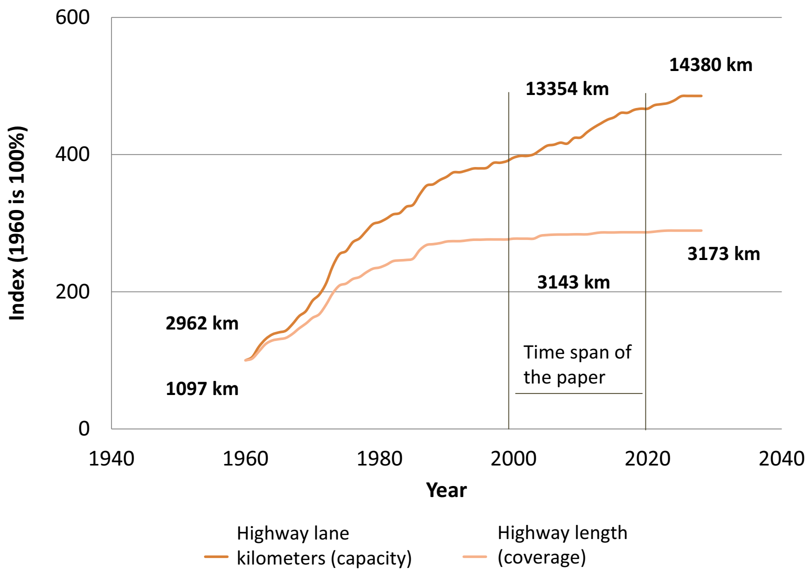

Figure 1. Highway length and lane kilometres.

kilometres. Highway length—that is, coverage—grew with a factor of 3 between 1960 and 1990 but did not increase substantially after 1990. In contrast, the number of lanes (i.e. road capacity)—and thus the number of lane kilometres—kept steadily rising. This figure also shows future plans: capacity is expected to keep growing in the coming years, whereas coverage remains almost stable. In this article, we focus on widenings in the period from 2000 to 2018, as indicated in the figure.

The Dutch have a long history in spatial planning. Similar to other European countries (e.g. the UK), the political decision-making concerning highway investments is very involved. Usually many years pass between the time a new highway corridor or widening is first mentioned in policy documents and the year of construction. Many rounds of consultations within different layers of the government, and with local residents, take place to ensure that most costs and benefits of new developments have been included.

The decision-making process includes six main steps before the project is carried out.[8] Several steps take quite some time and allow for appeal. It is therefore essentially impossible for governments and other decision-makers (e.g. commercial developers) to predict the exact *location and year* in which a highway widening will be opened (see also Hansen and Huang, 1997). For example, for widenings planned between 2000 and 2015 only 10% was realised in the planned year.[9] In total, 80% was delayed with up to 10 years and 10% was realised up to 5 years earlier than initially planned. Figure 2 shows a scatter diagram of the

8 (1) A Notice of Intent for the new widening is published. (2) Initial research examines the desirability of the widening. (3) An Initial Memorandum of Announcement is published which describes the need for and desirability of the investment. Local governments, interest groups and concerned citizens have the right to react. (4) The Memorandum is improved, in consultation with involved parties. An Environmental Impact Report is produced discussing different alternatives. (5) A draft Planning Approval Decision is written. Public consultation takes place again: lower governments, special interest groups and private citizens may offer input. (6) The Planning Approval Decision is announced. It is possible to appeal against this decision with the Council of State.

9 We calculate this using information on the realised and the planned opening year (as mentioned in the policy documents at the beginning of the decision-making process).

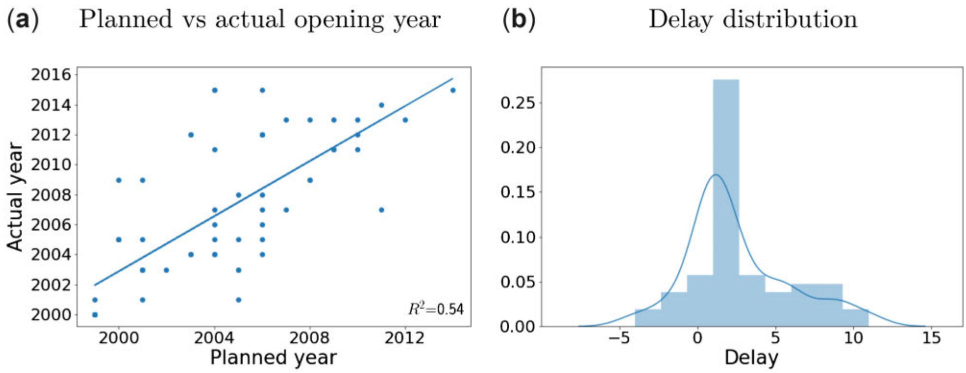

Figure 2. Highway widenings 2000–2015. The left panel is a scatterplot of the actual year of the opening of a widening on the planned year, for the highway widenings that were planned between 2000 and 2015. The right panel is a histogram of the delays, for the same set of widenings. The delays are calculated as the difference between the actual and the planned year.

realised and planned opening years (the R^2 of a linear relationship is only 0.54). We use this uncertainty surrounding the opening year for the purposes of identification.

Our study focuses on the Netherlands which has a dense highway structure with many ramps, so about 90% of Dutch households live within 2 km of a highway ramp.[10] As a result, the Netherlands has a high share of vehicle kilometres on highways (roughly 50% of overall vehicle kilometres)[11] and a corresponding low share of vehicle kilometres within cities (e.g. in Amsterdam, the number of car kilometres does not even exceed the number of bicycle kilometres). Using a congested highway is almost always faster than using an alternative uncongested non-highway route (Emmerink et al., 1996), which implies that non-highway roads tend to be complementary to highways.[12]

In contrast to most other countries, congestion is predominantly on highways between cities in the Netherlands. Within cities—which contain the bulk of non-highway roads—congestion is rather limited. This because of high parking prices, combined with low car speed levels due to the physical layout of roads, as over the last 40 years, road supply within cities has reduced for car users, whereas bicycle lanes have strongly increased.

In conclusion, highway widenings are unlikely to have a meaningful (negative or positive) effect on travel time on non-highway roads implying that the welfare gains or losses on these roads because of changes in congestion are of second order and can be ignored.[13] Furthermore, as it is plausible that non-highway roads are mainly complementary to highways, it is possible however that our welfare benefits of widenings are slight overestimates.

10 We have calculated this using the geocoded location of residences sold in the Netherlands.

11 We have calculated this using data from Statistics Netherlands.

12 This characteristic of the Netherlands is important, because the second-order welfare effects of highway widenings depend on the presence of time delays caused by car congestion on alternative routes to highways, which can be substitutes or complementary to highways. In case that roads are substitutes, travel time and flow on non-highway roads will be reduced by highway widenings, but if non-highway roads are primarily complementary, travel time and flow on non-highways will increase (Hsu and Zhang, 2014). These increases in travel time will typically lead to reductions in welfare, whereas the increases in flow will lead to increases in welfare, so the net second order effect is likely small and will be ignored.

13 This includes other travel externalities such as noise, see Ossokina and Verweij (2015), which are typically much smaller in magnitude than those caused by congestion.

3.2. Data on highway lanes, segments and widenings

We exploit information on the Dutch highway network in 2000–2018 collected by the Dutch Ministry of Infrastructure and Water Management. In total, 260 highway segments are distinguished in the network.[14] Within a segment, the number of lanes does not vary. We know for each segment its length (the average is 12 km), the number of lanes per year and therefore the year of the widening.

We focus on 48 widenings in the period from 2000 to 2018, which increased the total number of lane kilometres by almost 20%.[15] Most widenings have taken place in the west of the Netherlands, where most economic activity takes place. We have 16 widenings in 2013–2018 to study the effects on traffic outcomes.[16] For these widenings, we know the exact month of the widening. We also have information about another 32 widenings in 2000–2011 to study the effects on wider economic activity.[17] Supplementary Appendix A contains a full list of the widenings and their opening dates.

Figure 3 shows in blue the geographical location of the widenings used in the analysis of the traffic effects. To capture the traffic effects of widenings, we focus on the increase in lane kilometres within a certain region surrounding the widening. In our main analysis, these regions include highway segments within 20 km of the widening.[18] Traffic detectors located within this 20 km buffer are depicted in the plot in pink.

Greenfield highway construction may potentially interfere with widenings. During the period of investigation, there are only two new greenfields, both of a short length (7 and 4 km), so one expects that their influence is small, and maybe even negligible. Nevertheless, we predominantly focus on an area (shaded dark grey) that does not have any greenfield highway construction in a radius of 20 km within the period investigated. In our sensitivity analysis, we include observations located closer to greenfield construction.

Figure 4 shows in blue the geographical location of the widenings used in the analysis of the economic effects. Here, we focus on smaller regions around widenings, that is, on postal codes that experienced increases in lane kilometres within 10 km, where we distinguish between an increase of lane kilometres within 5 km as well as within 5–10 km from the widenings. Here, we again remove postcodes that had greenfield construction in the 20-km radius.

4. The effect of widenings on travel outcomes

4.1. Data

To study the effects of highway widenings, we employ high-frequency NDW data on car speed and car flow between 5:00 and 21:00 h obtained from individual induction loop traffic detectors on Dutch highways from July 2011 to November 2019.[19] Information is available on a minute basis for detectors. To reduce downloading and computation time,

14 A segment contains both driving directions.
15 We have excluded a few segments that experienced more than one widening or that received another treatment—for example, a peak lane opening.
16 Almost all of these widenings are located on highway segments situated in between larger cities.
17 We cannot use information on all 48 widenings to study their effects on traffic and economic activity outcomes, because the periods of observation of traffic and economic activity outcomes are both limited.
18 In the sensitivity analysis, we also show results for different geographical regions.
19 There is approximately one detector per 200 m highway in our data. NDW is an acronym for National Data Warehouse for traffic information.

Figure 3. Widenings 2013–2018. Traffic effect estimation. The figure depicts the widened segments included in the traffic effect estimation as well as the segments within a 20-km buffer from widenings. The dark grey shaded area does not contain any greenfield highway construction in a radius of 20 km during the study period.

we use information for a representative day of the week (Tuesday), and focus on monthly averages.[20]

Given information on speed, car flow for traffic detectors combined with distances between traffic detectors, we compute *travel time per kilometre* and *traffic flow*, that is, the number of vehicles per traffic detector for specific areas (e.g. within 20 km of a widening) per specific time interval (e.g. per hour or per day).[21] In total, we have information about 4500 detectors for 260 segments.

20 Analysis based on weekly data generates almost identical results.

21 Traffic flow (per detector) is proportional to the vehicle kilometres travelled (as the distance between detectors is of fixed length). Vehicle kilometres travelled is another popular measure used in this literature. As we will

Figure 4. Widenings 2000–2011. Economic effect estimation. The figure depicts the widened segments included in the economic effect estimation.

In our analysis, to reduce endogeneity issues, we focus on a subsample of some 250,000 monthly observations on travel time and traffic flow for 2560 individual detectors on 122 segments that are all within 20 km of a widening.[22] For the 16 segments that are widened we have information from 193 traffic detectors.

4.2. Descriptive statistics

Figure 5 shows monthly averages of log travel time and log traffic flow before and after the widening for treated segments.[23] This figure is helpful for our identification strategy. There are several messages in this figure.

First, due to road construction works, travel times increase and flow decreases temporarily for a period of about 2 years before the widening (see also Kim, 2022). Second,

use detector-specific information and use log transformations, our results for traffic flow can be interpreted as the results for vehicle kilometres travelled.

22 Traffic detector data are not always available, for example, because of malfunctioning. We require detectors to have at least 42 months of data. Furthermore, we only select detectors of widened segments for which we have at least 30 months of data before and at least 12 months of data after the widening.

23 These variables are detector-demeaned.

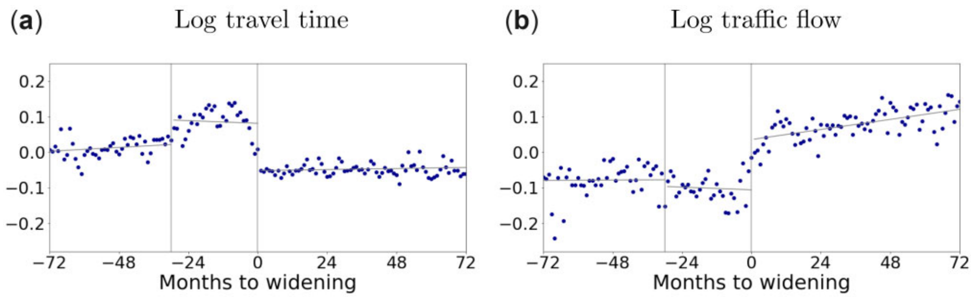

Figure 5. Time dynamics of traffic activity on widened segments. Plotted values are detector-demeaned logarithm travel time and logarithm traffic flow on the widened segments, in the time period ranging between 6 years (72 months) before the widening and 6 years (72 months) after the widening. The vertical lines indicate the start and end of the construction works preceeding the opening of a widening.

excluding the construction period, travel times are substantially lower after the widening. Third, before the widening but also after the widening, travel time is approximately constant. For example, 6 years after a widening, the travel time is roughly the same as after 2 years. Fourth, ignoring the construction period, traffic flow is approximately constant over time before the widening. It strongly increases in the first 2 years after the widening, whereas this increase seems to level off after 4 years.

Table 1 left panel reports descriptive statistics on the widened segments for two specific moments: 3 years before and 2 years after the widening.[24] Here, we also distinguish between different time windows within the day. It shows that widenings imply a substantial increase in the number of lanes (from 4.4 to 6.5 lanes). This goes together with a 25% decrease in travel time during peak hours and a 10% decrease in travel time over the day. These travel time decreases go along with flow increases of 25% in the peak and 15% over the day.

These descriptives for widened segments also indicate that segments have not been randomly widened. Road capacity was increased through widenings in order to reduce time delays due to bottlenecks present during peak hours: widened segments have higher travel times during peak hours before the widening (about 50 s/km) compared with segments that have not been treated (about 44 s/km), but this is not true for travel times averaged over the day, as daily travel times are about equal for widened and non-widened segments (equal to about 39 s/km). This observation is key input for our welfare analysis. It suggests that the Dutch government has widened highway segments where the economic benefits of widenings are potentially the largest.

Table 1 middle and right panel reports descriptive statistics for traffic activity at the level of the region—for the main analysis as well as the analysis where we include observations nearby (within 20 km) two greenfield highways—for the beginning (2011) and the end of the observation period (2019).[25] It shows a strong increase in

24 We focus on these specific moments, because only then we have full information for all widenings. For example, 6 years after the widening, we only have information about 5 of the 16 widenings.

25 We focus on regions that may have received several widenings with substantial variation in the increase in lane kilometres. Therefore, it is insightful to provide descriptive information about the beginning (2011) and the end of the observation period (2019) and less informative to use 'event study' types of figures such as Figure 5.

Table 1. Data descriptives traffic outcomes, 2011–2019

	Widened segments		Main analysis		Greenfields nearby	
	3-year before	2-year after	2011	2019	2011	2019
Number of lanes	4.39	6.51				
	(0.86)	(1.14)				
Lane kms radius 0–20 km			622.45	689.02	735.02	810.88
			(143.09)	(180.36)	(206.85)	(247.27)
Travel time 7:00–9:00 h	50.60	37.50	44.28	43.55	44.62	43.92
	(30.93)	(18.58)	(17.29)	(15.43)	(17.84)	(14.89)
Travel time 6:00–10:00 h	45.04	36.91	41.55	41.00	42.01	41.50
	(21.43)	(28.59)	(12.09)	(10.94)	(12.72)	(10.81)
Travel time 5:00–21:00 h	39.88	36.33	39.11	39.33	39.78	40.14
	(9.62)	(27.94)	(7.18)	(6.86)	(7.62)	(7.43)
Traffic flow 7:00–9:00 h	3.26	4.01	2.71	3.16	2.93	3.30
	(1.00)	(1.34)	(1.14)	(1.35)	(1.35)	(1.45)
Traffic flow 6:00–10:00 h	2.87	3.40	2.39	2.82	2.59	2.95
	(0.92)	(1.18)	(1.04)	(1.23)	(1.22)	(1.30)
Traffic flow 5:00–21:00 h	2.46	2.80	2.03	2.37	2.20	2.49
	(0.85)	(0.96)	(0.81)	(0.96)	(0.96)	(1.04)
Number of segments	16		69		122	
Number of detectors	193		1403		2561	

Notes: We show means and standard deviations *per detector*. Number of lanes is in both directions. Travel time is measured in seconds per kilometre. Traffic flow is measured in 1000 vehicles per hour.

lane kilometres because of widenings: lane kilometres increase by about 10% between 2011 and 2019.[26]

4.3. Empirical model and identification

We denote our two traffic measures—log travel time per kilometre and log flow—at a (traffic detector) location l of an area s, in month t by V_{lst}. An area can either refer to a segment or a region (which contains locations within 20 km of location l). To examine the dynamic effects of changes in highway lane length induced by widenings on traffic within an area, we use a distributive lag specification allowing for effects starting 3 years before the widening up to 6 years after a widening:

$$V_{lst} = \sum_{L=-3}^{6} \alpha_L H_{s,t-12L} + \delta_l + \phi(t) + \xi_{lst}, \qquad (1)$$

where $H_{s,t-12L}$ denotes the log of highway lane length in area s in the month $t-12L$, where L denotes a year and takes values from -3 until 6; δ_l denotes detector fixed effects; $\phi(t)$ denotes year and month-of-the-year fixed effects and ξ_{lst} is an error term. So, for example, if $L=-1$, then we measure the effect of highway lane length as observed exactly 12 months before t.

26 This table also shows slight decreases in peak hour travel time over this period, with increases in travel time over the full day and considerable increases in flow particularly during the peak. Clearly, the latter information is not indicative of a causal effect of widenings, for example, because it ignores autonomous time trends.

The above specification allows the effects of highway lane length increased by widenings to vary by year around the widening. The latter is important for two reasons. First, one expects that the effect of increased kilometre length varies over time after the widenings. Second, because of construction work, widenings may already have effects before their openings. Hence, in Equation (1), we account for the confounding bias effects of construction works before the widening by including lead variables for the 3 years before the widening: $H_{s,t+12L}$, $H_{s,t+24L}$ and $H_{s,t+36L}$. In other words, this setup allows us to compare the two traffic measures during two periods: the period after a widening with the period more than 3 years before the widening.

The discussed empirical strategy is essentially a two-way fixed effects, where we include year, month-of-the-year and location fixed effects, which rely on a common trends assumption. As highways are widened because of travel delays, it is possible that this assumption does not hold, that is, it may be the case that the trend in travel delays and flow differs between widened and nonwidened highways. To deal with this, we will include only highway segments that are within 20 km of segments that are widened at least once. Hence, the identifying assumption of common trends is relaxed.

In the above specification, we assume that $H_{s,t-12L}$ changes for exogenous reasons. We have argued in Section 3 that this is plausible because the timing, that is, the specific year, of the widening is highly random. Still, one may be worried that unobserved factors correlated to the 'dose' of the widening, that is, the increase in number of lane kilometres given a widening, are correlated to the observed traffic outcomes, thus inducing omitted variable bias.

We will address this issue by employing an IV strategy. We use as instrument an indicator capturing the number of widenings in the area surrounding a detector since the start of the study period. The value of the instrument is therefore detector and year specific. Given detector fixed effects, this instrument essentially captures whether in a specific year there was at least one widening. By construction, the instrument is not related to the 'treatment dose', as it does not depend on the number of kilometres lane added. So, it takes the same value whether a widening involves adding one or two lanes of a specific kilometre length, or whether a widening involves adding few or many kilometres. Furthermore, the instrument is strong, as an increase in the value of the instrument is strongly correlated with an increase in lane kilometres.

We are interested in the effect of widenings on travel time per kilometre per motorist. For that reason, the effect of widenings on travel time is estimated using a weighted regression, with weights based on the (time-invariant) average flow per traffic detector, where the average is taken over the whole study period.

We will estimate α_L, which is equal to the elasticity of the traffic outcomes with respect to highway lane length L years after the widening, conditional on highway length in other years.[27] We are particularly interested in the widenings' *cumulative effect M* years after a widening, that is, in $\sum_{L=0}^{M} \alpha_L$ for values of M from 0 up to 6.[28] This latter cumulative coefficient

27 Because V_{lst} and $H_{s,t-12L}$ are in logarithms, $\alpha_L = \partial V_{lst} / \partial H_{s,t-12L}$.

28 $\sum_{L=0}^{M} \alpha_L$ can be obtained by summing the values for α_L after estimating Equation (1). Conveniently, $\sum_{L=0}^{M} \alpha_L$ can also be estimated directly by rewriting Equation (1) as:

$$V_{lst} = \sum_{L=0}^{6} \alpha_L H_{s,t-12L} + \sum_{L=-3}^{-1} \alpha_L H_{s,t-12L} + \delta_l + \phi(t) + \xi_{lst} \tag{2}$$

and where the first summation can be decomposed into:

will be reported in the preferred specifications, while α_L will be reported in the Supplementary Appendix. Further, we report standard errors of the estimate of $\sum_{L=0}^{M} \alpha_L$ clustered at the segment level s and run robustness checks with HAC standard errors which allow for arbitrary correlation of residuals over space (both yield very similar results).

It is plausible that the effects of widenings strongly differ over the day: widenings are usually motivated by travel delays during peak hours, so they are expected to have the largest travel time reducing effects in the peak, and smaller effects during the rest of the day. Furthermore, given these reductions in travel time, one expects that motorists will substitute their chosen travel hour during the day towards the peak. We therefore distinguish between three time windows following definitions of the Ministry of Infrastructure and Water Management: 7:00–9:00 (narrow morning peak), 6:00–10:00 (broad morning peak) and 5:00–21:00 (entire day).[29]

4.4. Empirical results

4.4.1. Local effects

We here focus on the local effects of widenings, so at the segment level. Table 2 reports the estimated effects of a local increase in log highway lane kilometres on travel time as well as on flow in the Lth year after the widening *compared with the period that ends 3 years before the widening*.[30]

The widenings have immediate large effects. For example, immediately after the opening, travel time during the narrow peak (7:00–9:00) decreases by about 50%, whereas travel demand increases by about 35%.

It appears that widenings also have persistent effects on local traffic. For the full day (between 5:00 and 21:00), the elasticity of travel time with respect to highway supply is –0.54 after 6 years. During peak hours, the elasticity of travel time is approximately the same, but only for the first years after the widenings is this elasticity precisely estimated. We find also very strong effects of highway supply on traffic flow with an elasticity of about 0.2 for the full day, and a somewhat larger elasticity during the peak. The latter estimated effects are highly statistically significant up to 5 years after the opening. Only in the last year, standard errors become large, because we do not have enough widenings to estimate the effects precisely.

These results provide insight into various behavioural substitution mechanisms that are at play. First, an increase in traffic flow is in line with motorists' substitution from other

$$\sum_{L=0}^{6} \alpha_L H_{s,t-12L} = \beta_6 H_{s,t-12*6} + \sum_{M=0}^{5} \beta_M \left[H_{s,t-12M} - H_{s,t-12(M+1)} \right], \qquad (3)$$

where $\beta_M = \sum_{L=0}^{M} \alpha_L$ and β_6 is defined accordingly.
Consequently, after substituting Equation (3) into Equation (2), and then by estimating Equation (2), one obtains $\beta_M = \sum_{L=0}^{M} \alpha_L$ directly. This effect we will report in the main text. We report the full results from estimating Equation (1) in Supplementary Appendix B.

29 We also did estimations for the evening peak, these are available upon request.

30 Supplementary Appendix B reports the α_L of Equation (1). It is shown there that road construction has a sizeable effect on travel time as well as traffic flow at the segment level (in line with Kim (2022) who shows that this effect is temporary). Note again that, by construction, results in Table 2 compare the traffic after the widening with the traffic before the start of the roadworks. Supplementary Appendix C reports a sensitivity analysis with HAC standard errors.

Table 2. Traffic effects on widened segments

Dependent	Log travel time			Log traffic flow		
	7:00–9:00	6:00–10:00	5:00–21:00	7:00–9:00	6:00–10:00	5:00–21:00
year widening	−0.543***	−0.444***	−0.319***	0.344***	0.263***	0.240***
	(0.094)	(0.066)	(0.041)	(0.069)	(0.059)	(0.048)
1 year after	−0.500***	−0.400***	−0.334***	0.322***	0.262***	0.230***
	(0.150)	(0.117)	(0.052)	(0.081)	(0.060)	(0.056)
2 years after	−0.498**	−0.428***	−0.379***	0.365***	0.298***	0.241***
	(0.199)	(0.166)	(0.075)	(0.104)	(0.073)	(0.071)
3 years after	−0.531**	−0.440**	−0.419***	0.337***	0.267***	0.224***
	(0.255)	(0.209)	(0.090)	(0.118)	(0.087)	(0.083)
4 years after	−0.511	−0.418	−0.450***	0.265*	0.218**	0.216**
	(0.313)	(0.266)	(0.108)	(0.154)	(0.110)	(0.098)
5 years after	−0.552	−0.479	−0.534***	0.327*	0.262**	0.223**
	(0.389)	(0.334)	(0.136)	(0.177)	(0.115)	(0.107)
6 years after	−0.434	−0.392	−0.541***	0.201	0.166	0.166
	(0.436)	(0.381)	(0.162)	(0.223)	(0.150)	(0.120)
Detector FE (193)	Yes	Yes	Yes	Yes	Yes	Yes
Month FE (12)	Yes	Yes	Yes	Yes	Yes	Yes
Year FE (9)	Yes	Yes	Yes	Yes	Yes	Yes
Observations	18,761	18,782	18,780	18,761	18,782	18,780
R^2	0.289	0.327	0.457	0.473	0.413	0.576

Notes: The independent variable is log lane kilometres in the segment in which a detector is located, per year. The columns report the estimates of a change in log lane kilometres for the narrow morning peak (7:00–9:00), the broad morning peak (6:00–10:00) and the entire day (5:00–21:00) compared with the period that ends 3 years before the widening. Estimates for the evening peak are available upon request. The effects on travel time are estimated using a weighted regression, with weights based on the (time-invariant) average flow, where the average is taken over the whole study period. We cluster standard errors at the segment level. Standard errors are in parentheses. *, ** and *** represent 10%, 5% and 1% significance, respectively.

routes (and potentially the overall increase in car travel demand). Second, the increase in out-of-peak flow is less than that during the peak, providing evidence for substitution within the day (Arnott et al., 1990, 1993; Small et al., 2005). In other words, motorists reschedule their travel to the peak times as the latter become less congested.

Above estimates are also politically important. They show that highway widenings are *locally* extremely effective in reducing travel delays. This explains why highway widenings are a popular tool for politicians who aim to address congestion (Glaeser and Ponzetto, 2018), whereas road pricing is not popular at all, as most motorists are worse off (Russo, 2013).

We have estimated the effects of widenings on traffic flow as well as on travel time at the detector level. The ratio of these two elasticities can be interpreted as the elasticity of flow to travel time. Our estimates suggest that the implied elasticity is around −0.75 immediately after the widening, getting smaller in absolute value in later years.[31]

31 Note that in the empirical speed-flow literature *at the detector level*, studies focus on the *supply* relationship between travel time and flow in order to estimate the marginal external cost of congestion (Yang et al., 2020; Russo et al., 2021). In contrast, our ratio captures a *demand* relationship between travel time and flow, that is

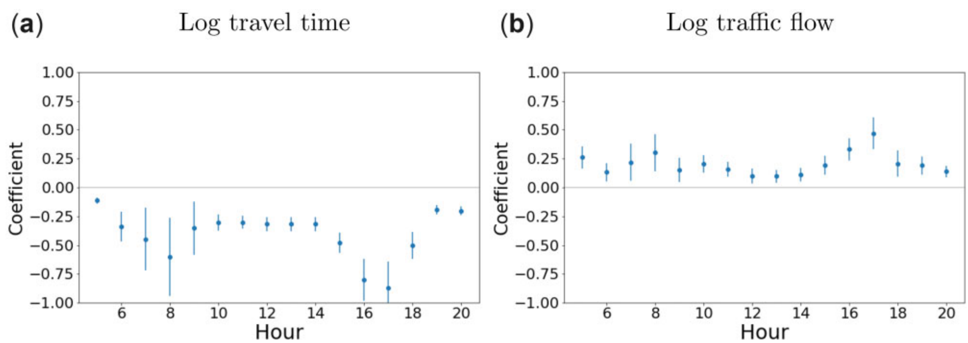

Figure 6. Hourly elasticities, widened segments, 4 years after widening. Plotted values are hourly elasticities and 95% confidence intervals, obtained from similar regressions as in Table 2, run separately for each hour of a day between 5:00 and 21:00.

To improve our understanding into the substitution effects within a day, we estimate the travel time and flow elasticity for each hour of the day. Figure 6, which shows these results for the 4th year after the opening, supports the above insights. All travel time elasticities are negative and the effects are most pronounced during the (evening) peak. For flow, the variation in the effects over the hour of the day is less pronounced, but also here we see stronger increases during the (evening) peak.

4.4.2. Regional effects

Table 3 reports the effects of widenings at the level of the region. Hence, it reports the estimated effects of a regional increase in log highway lane kilometres on travel time as well as on flow in the *L*th year after the widening *compared with the period that ends 3 years before the widening*.[32] The results show large and persistent reductions in travel time in the region, with an elasticity of around –0.70 in the 6th year after the widening. During peak hours, the travel time effects are the largest in the first year after the widening, and decrease by one-third after, in line with the increasing travel demand. For the full day, the decrease in travel time is much less notable.

Widenings have a strong positive effect on traffic flow. The size of the estimated effects increases in the first 3 years and then stays approximately the same. This result is consistent with the idea that the induced demand is a gradual process, as it takes time for households and firms to re-optimise their location and travel patterns, for which we show evidence later on (Section 6). There are substantial increases in travel demand during the narrow peak, with an elasticity of about one (1.03) 6 years after the widening. Interestingly, the null hypothesis of a unit elasticity cannot be refuted already 1 year after the widening (with an estimate of 1.06). For the entire day, the effect is half as large with an elasticity of 0.52, so below 1.

estimated at the detector level, which is by itself less useful for economic analysis and therefore ignored in the speed-flow literature. Nevertheless, our estimates are comparable to the values found by Kim (2022) as well as the results of earlier studies (see overview in Kim, 2022).

32 Supplementary Appendix B reports the α_L of Equation (1). We have also estimated models with other specifications, including linear models (see Supplementary Appendix D). Linear specifications yield similar implied elasticities. This result is relevant as for linear models, estimates at the individual detector level can be interpreted as estimates at the aggregate level.

Table 3. Traffic effects region

Dependent	Log travel time			Log traffic flow		
	7:00–9:00	6:00–10:00	5:00–21:00	7:00–9:00	6:00–10:00	5:00–21:00
year widening	−0.930***	−0.814***	−0.500***	0.225	0.088	−0.001
	(0.359)	(0.268)	(0.161)	(0.155)	(0.130)	(0.115)
1 year after	−1.332***	−1.192***	−0.848***	1.064***	0.772***	0.560***
	(0.474)	(0.370)	(0.252)	(0.257)	(0.218)	(0.182)
2 years after	−1.134**	−1.036**	−0.779***	1.267***	0.975***	0.699***
	(0.525)	(0.402)	(0.264)	(0.298)	(0.256)	(0.219)
3 years after	−0.804	−0.786*	−0.550**	1.093***	0.826***	0.524***
	(0.555)	(0.428)	(0.242)	(0.274)	(0.234)	(0.196)
4 years after	−0.846	−0.801*	−0.564**	1.119***	0.850***	0.625***
	(0.596)	(0.451)	(0.267)	(0.300)	(0.261)	(0.220)
5 years after	−0.962	−0.903**	−0.652**	1.030***	0.763***	0.434*
	(0.596)	(0.456)	(0.269)	(0.306)	(0.261)	(0.222)
6 years after	−0.785	−0.781*	−0.680**	1.029***	0.774***	0.515**
	(0.589)	(0.452)	(0.293)	(0.345)	(0.295)	(0.252)
Detector FE (1403)	Yes	Yes	Yes	Yes	Yes	Yes
Month FE (12)	Yes	Yes	Yes	Yes	Yes	Yes
Year FE (9)	Yes	Yes	Yes	Yes	Yes	Yes
Observations	140,534	139,789	140,825	140,534	139,789	140,825
R^2	0.109	0.119	0.162	0.162	0.168	0.179

Notes: The independent variable is log lane kilometres in a 20-km buffer surrounding a detector, per year. The columns report the estimates of a change in log lane kilometres for the narrow morning peak (7:00–9:00), the broad morning peak (6:00–10:00) and the entire day (5:00–21:00) compared with the period that ends 3 years before the widening. Estimates for the evening peak are available upon request. The effects on travel time are estimated using a weighted regression, with weights based on the (time-invariant) average flow, where the average is taken over the whole study period. Standard errors (clustered at segment level) are in parentheses. *, ** and *** represent 10%, 5% and 1% significance, respectively.

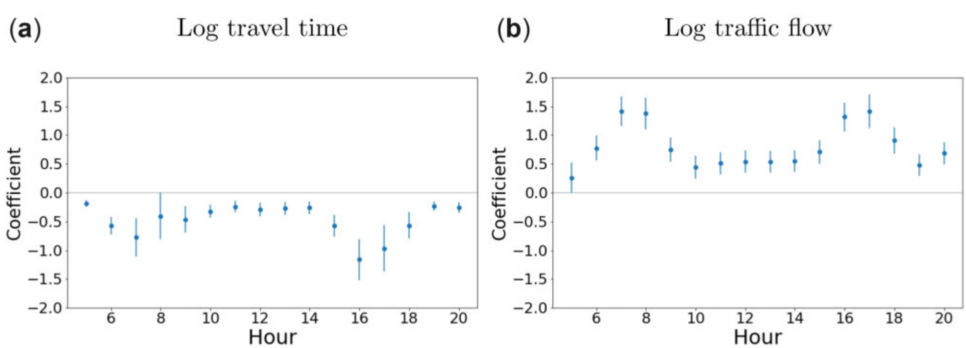

Figure 7. Hourly elasticities, region, 6 years after widening. Plotted values are hourly elasticities and 95% confidence intervals, obtained from similar regressions as in Table 3, run separately for each hour of a day between 5:00 and 21:00.

To improve our understanding of the substitution effects occurring within a day, we again estimate the effects on travel time and flow elasticities by the hour of the day for the 6th year after the widening. The effects by hour of the day reported in Figure 7 support the insights from Table 3. The travel time elasticities are negative and statistically significant for all hours of the day, with the effect being more pronounced during the peak hours, particularly the evening peak. Correspondingly, the flow elasticities are positive, and much higher during the morning and evening peak.

We have argued above that highways within regions tend to be complementary, and not substitutes. To examine this, we have re-estimated the models at the regional level (i.e. within 20 km of the widening), where we exclude segments that have been widened. These results can be found in Table E1 of Supplementary Appendix E. The estimated flow elasticities of widenings are shown to be positive, and somewhat smaller than those reported in Table 3. This indicates that highways within regions are highly complementary, so highways feed into each other.

Widenings aim to remove bottlenecks within networks, but they may induce new bottlenecks in other parts of the network where demand has increased. If this is the case, then travel times in other parts of the network should increase. In contrast, the removal of a bottleneck of a certain segment may reduce travel time of nearby segments when queues extend to other segments. We test for these hypotheses by examining the effects of widenings on travel time in nearby segments (see Table E1 of Supplementary Appendix E). It appears that the effect of widenings is negative (and statistically significant for the first 3 years). This strongly suggests that widenings did not cause new bottlenecks in other parts of the network.

To account for the possible endogeneity of the 'treatment dose' of a widening, we perform an instrumental variable (IV) analysis. We instrument the number of lane kilometres with an indicator capturing the number of widenings in the 20-km buffer surrounding the detector since the start of the study period. The instrument—number of widening events—is strong (with an F-value above 100). Table 4 reports the results of the second stage. The point estimates are similar, and typically somewhat larger in absolute value, to those of the baseline, but with larger standard errors, hence for the later years, not all coefficients are statistically significant at conventional significance levels. However, IV estimates cannot be distinguished from OLS estimates using Hausman t-tests.

Summarising, our results imply that widenings reduced congestion in the short run (at least within 6 years). This reduction occurred on the widened segments by resolving the bottlenecks, but also improved traffic conditions on complementary highways. Although the widenings induced an increase in traffic, this was by far not strong enough to eliminate the travel time benefits. This insight is important and complements previous studies that focus on the long-run effects of highways arguing that highways do little or nothing to reduce travel time in the long run. Our results suggest the presence of short-run benefits that may justify the widenings investment costs, even if the time savings should disappear in the long run. In Section 5, we will compare the welfare costs and benefits of widenings, allowing us to calculate the overall effect.

4.4.3. Sensitivity analyses

We have subjected our results to a range of sensitivity analyses such as the calculation of the standard errors, the functional form, the definition of the region, the chosen subsample, the inclusion of additional time trend control variables and including detectors that lie within 20 km distance from the two greenfield highway links.

In Supplementary Appendix C, we re-estimate models with Heteroskedasticity and Autocorrelation Consistent (HAC) standard errors. It appears that standard errors are very

Table 4. Traffic effects region: IV

Dependent	Log travel time			Log traffic flow		
	7:00–9:00	6:00–10:00	5:00–21:00	7:00–9:00	6:00–10:00	5:00–21:00
year widening	−0.995**	−0.862***	−0.389**	0.603**	0.421*	0.192
	(0.419)	(0.320)	(0.185)	(0.279)	(0.225)	(0.193)
1 year after	−1.990***	−1.670***	−0.957***	1.419***	1.058***	0.637**
	(0.756)	(0.568)	(0.361)	(0.405)	(0.313)	(0.253)
2 years after	−1.630*	−1.386**	−0.842**	1.621***	1.308***	0.811***
	(0.839)	(0.625)	(0.383)	(0.454)	(0.356)	(0.293)
3 years after	−1.404*	−1.217*	−0.672*	1.342***	1.070***	0.567*
	(0.852)	(0.634)	(0.404)	(0.469)	(0.363)	(0.294)
4 years after	−1.363	−1.144	−0.635	1.253**	1.028**	0.625*
	(0.955)	(0.708)	(0.475)	(0.558)	(0.452)	(0.375)
5 years after	−1.553*	−1.288*	−0.692	1.174**	0.958**	0.440
	(0.929)	(0.691)	(0.466)	(0.548)	(0.439)	(0.359)
6 years after	−1.472	−1.233	−0.723	1.134*	0.934*	0.448
	(1.018)	(0.756)	(0.511)	(0.607)	(0.488)	(0.406)
Detector FE (1403)	Yes	Yes	Yes	Yes	Yes	Yes
Month FE (12)	Yes	Yes	Yes	Yes	Yes	Yes
Year FE (9)	Yes	Yes	Yes	Yes	Yes	Yes
Observations	140,534	139,789	140,825	140,534	139,789	140,825

Notes: The independent (instrumented) variable is log lane kilometres in a 20-km buffer surrounding a detector, per year. The instrument is the cumulative number of widening events a detector has experienced between the start of the study and year *t*. The columns report the estimates for the narrow morning peak (7:00–9:00), the broad morning peak (6:00–10:00) and the entire day (5:00–21:00) compared with the period that ends 3 years before the widening. The effects on travel time are estimated using a weighted regression, with weights based on the (time-invariant) average flow, where the average is taken over the whole study period. Standard errors (clustered at segment level) are in parentheses. *, ** and *** represent 10%, 5% and 1% significance, respectively.

similar. In Supplementary Appendix D, we re-estimate the effects using a linear specification of regional travel time/flow and number of lane kilometres rather than a log–log specification. It appears that specifications yield similar implied elasticities, if we use the means of the variables. This result is relevant as for linear models, estimates at the individual detector level can be interpreted as estimates at the aggregate level, whereas this result does not hold for log–log models. Consequently, our estimates seem to hold at different levels of aggregation.

We have re-estimated all models using a different definition for region (Supplementary Appendix F). To be more precise, in Supplementary Table F1, we have examined the effects on traffic outcomes within 10 km of a widening (rather than within 20 km of a widening). The flow elasticities of widenings within 10 km are the same, but the travel time elasticities are larger.

Recall that we have focused solely on segments, respectively, regions where road capacity increased during the study period. Arguably, this makes the estimation procedure more convincing, as it relaxes the parallel trend assumption. Nevertheless, we have also re-estimated the models by including the full sample for the Netherlands, rather than a sample of detector observations within 20 km of a widening, almost quadrupling the number of observations. The results are reported in Tables F2 and F3 of Supplementary

Appendix F. Point estimates of the effects on flow are somewhat larger and of travel time somewhat smaller. However, they do not show a meaningful difference with the baseline results. Hence, the results remain robust, providing more confidence in the estimation procedure.

Assumptions about the underlying time trend are fundamental to our analysis. We have therefore re-estimated the models by including a linear time trend interacted with province (in the Netherlands there are 12 provinces, but treated areas include only 6 provinces), see Supplementary Tables E2 and F4. It appears that the results for the first 4 years after the widening are extremely robust, but point estimates for the years after are noninformative, because of large standard errors. This makes sense as we have fewer observations after 6 years. Both, the results for the detectors within 20 km from the treated segments and the results for the whole country, are robust.

Finally, Supplementary Table E3 reports the effects of widenings when also including the detectors that lie within 20 km distance from the two greenfield highway links (see Figure 3). The results show large and persistent reductions in travel time in the region, with an elasticity of around −0.6 in the 6th year after the widening. The elasticity is very close to that obtained before, also the dynamic effects are the same. During peak hours, the travel time effects are the largest in the first year after the widening, and decrease by one-third after, in line with the increasing travel demand. For the full day, the decrease in travel time is much less notable. The point estimate of the effect on flow is now larger, but the difference is not statistically significant. Furthermore, we do not reject anymore the null hypothesis of unity elasticity for the full day. Finally, we have repeated all previous sensitivity analyses for the latter sample. It appears that we come to the same conclusion when we include observations near these greenfield highway links (results can be received upon request).

5. Welfare effects

In this section, we apply the results of the above analysis to compute the welfare effects of the widenings that opened between 2013 and 2018. We focus on the short-run benefits, that is, benefits that occur during the first 6 years after the widenings. So we limit our calculation to provide an estimate of which share of the widenings' costs is covered by the short-run benefits.

In the cost–benefit calculation, we account for the investment and maintenance costs, the travel time benefits and the benefits from rescheduling. Further, we include the travel time losses on widened segments during construction and allow for the benefits from improved reliability of the travel time (Small et al., 2005).[33]

5.1. Theory

Let us compute the daily consumer surplus effect obtained on a highway link covered by detector l, due to *travel time gains* in year y after a widening within the region (i.e. within

33 We ignore the travel time losses during construction which may occur on adjacent segments as our estimates suggest these are likely small. We also leave out the effect of widenings on local environmental quality by assuming that the excise duties and other indirect fuel taxes are set optimally, so that the marginal excise tax on gasoline exactly equals the external effect of an additional kilometre travelled. Note furthermore that while an increase in highway travel generally suggests a negative welfare effect, previous studies show that this needs not necessarily be the case. Highway construction may, for example, yield substantial benefits from relieving local streets from through traffic (Ossokina and Verweij, 2015).

20 km of l). We denote the effect by $\triangle W_l(y)$. For now, we ignore rescheduling within the day, consequently we ignore differences between peak and nonpeak hours demand. We assume that the daily demand function can be approximated by a linear function, which allows for the following approximation (see e.g. Williams (1976) for formal derivation, replicated in short in Supplementary Appendix G):

$$\triangle W_l(y) = [V_{l0}(y)(t_{l0}(y) - t_{l1}(y)) + 0.5(V_{l1}(y) - V_{l0}(y))(t_{l0}(y) - t_{l1}(y))]\text{VOT}, \quad (4)$$

Here, t_{l0} and t_{l1} refer to before-the-widening and after-the-widening travel times, respectively. V_{l0} and V_{l1} refer to before- and after-the-widening daily traffic flows, respectively, multiplied with the highway length in kilometres covered by a specific detector. VOT refers to the value of time per car.

The first term $V_{l0}(y)(t_{l0} - t_{l1})$ reflects the welfare benefits due to shorter travel times, for motorists who used the route before the widenings. The second term $0.5(V_{l1} - V_{l0})(t_{l0} - t_{l1})$ reflects the (smaller) travel time benefits due to the widenings-induced increase in travel demand.

One may extend the above calculation by allowing for *hourly* rescheduling within the day, as we have hourly observations. However, it appears that the additional benefits of rescheduling within the day are almost negligible, so this issue is further ignored.

The annual welfare effect is then calculated by multiplying $\triangle W_l$ with the number of days in a year, denoted by d, and by summing the effects over all detectors. We will discount the future at the discount rate ρ. The present value of the total welfare effect, $\triangle W$, is therefore calculated as follows:

$$\triangle W = \sum_y \frac{1}{(1+\rho)^y} \triangle W(y) = \sum_y \frac{d}{(1+\rho)^y} \sum_l (\triangle W_l(y)). \quad (5)$$

5.2. Numerical assumptions

The travel time and flow before the widening are derived from the observed data in 2011. The travel time and flow after the widening are counterfactuals, calculated for the year of the widening ($y = 0$) and each of the six subsecutive years, using the point estimates from Table 3. We further allow for an autonomous increase in flow as implied by the model estimates.[34] It is further assumed that the welfare benefits of the widenings only apply to working days, thus ignoring the benefits in the weekends. As congestion in the weekends is much less than during workdays, this is unlikely to be fundamental. The number of working days in a year is assumed to be 256. To translate time savings into welfare benefits, a value of time per car of 20 euro/hour is used (similar to Adler and van Ommeren (2016), average over different travel motives).

Our data do not allow to estimate reliability benefits directly using the value of reliability as Brownstone and Small (2005) suggest. So, we use another approach based on a paper by Van der Loop et al. (2014) in which reliability benefits were calculated for a large number of Dutch highway projects (greenfield and widenings) implemented from 2001 to 2011. The article finds the reliability benefits to be in the order of magnitude of 20% of the travel time benefits. Because in our article we only focus on widenings and

34 It appears that there is growth in each year; over the period 2011–2019, the accumulated growth is about 15%.

not greenfield, we take the reliability benefits to be half of what Van der Loop et al. (2014) reports: 10% of the travel time savings.

Construction cost per lane is assumed to be 5 million euro per lane kilometre.[35] After the opening of a widening, yearly maintenance costs are equal to 2% of the investment costs (according to the rules used by the Ministry of Infrastructure and Water Management).

To calculate the present value of the welfare effects, a discount rate of 2.25% is applied, which is the prescribed discount rate in the Dutch cost–benefit analyses of transportation investments. Finally, we assume that the excise duties and other indirect fuel taxes are set optimally, so that the marginal excise tax on gasoline exactly equals the external effect of an additional kilometre travelled.[36] We ignore other possible tax distortions, such as subsidies to company cars, free parking et cetera.

5.3. Welfare outcomes

Table 5 reports the descriptives of the observed traffic outcomes ('before widening') and counterfactual traffic outcomes ('6 years after a widening') per detector. It shows that the widenings resulted in an increase from 727 to 780 lane kilometres within a 20-km radius per detector, so by about 7%. In total, about 400 new lane kilometres were constructed, resulting in an investment of about 1970 million euro. This leads to a counterfactual 3% decrease in the travel time (from 41.3 to 40.1 s/km) and a counterfactual induced demand of 4% (from 2180 to 2270 cars per hour).

Table 6 reports the calculated welfare effects from widenings based on the OLS results reported in Table 3. Almost identical results are obtained with IV estimates. The maintenance costs over 6 years are computed to be about 250 million euros, so the total investment and maintenance costs are about 2220 million euros. The accumulated benefits after 6 years are worth about 909 million euros, which predominantly consists of time savings. This implies that about 40% of the investment and maintenance costs are recovered within the first 6 years after the widening.

We can only speculate about the welfare implications in the long run. One plausible scenario is to assume that the fundamental law of road congestion holds in the long run, for example, 20 years, such that the time savings disappear and induced demand increases in proportion to the extended road lanes. Given this scenario, our estimates imply that the average widening has not been welfare beneficial. However, the fact that traffic flows and travel times don't show a clear increasing, respectively, decreasing trend during the 6 years we study, seems to imply the effects could last much longer. Therefore, another plausible scenario is to assume that the estimates do not change after 6 years. In that case, the average widening is welfare beneficial after about 20 years.

6. Economic activity and spatial structure

Widenings are thought not only to reduce travel time, but also to affect wider economic activity and therefore the spatial structure of employment and population. These effects

35 The costs per lane kilometre are derived from two-lane widening estimates provided by the Ministry of Infrastructure and Water Management for 110 km lanes that are planned for the coming years. Note that widenings are much cheaper than greenfield construction. The cost of a lane kilometre of a widening is roughly one-fourth of the cost of a greenfield extension.

36 Existing Dutch cost–benefit analyses of highway investments suggest that the excise duties are higher than the external effects of kilometres travelled in the Netherlands, this would imply that we underestimate the benefits.

Table 5. Descriptives of observed (before widening) and counterfactual outcomes

	Before widening (observed)		6 year after widening (counterfactual)	
	Mean	St. Dev.	Mean	St. Dev.
Lane kms within 20 km	727.37	(210.66)	780.54	(226.89)
Travel time	41.33	(5.04)	40.06	(4.91)
Traffic flow	2.18	(0.73)	2.27	(0.83)

Notes: Descriptives per detector, daily average. Travel time is measured in seconds per kilometre. Traffic flow is measured in 1000 vehicles per hour. The counterfactual values for travel time and flow have been computed using the observed change in lane kilometres and the coefficients estimated in the previous section.

Table 6. Welfare effect widenings after 6 years

(i)	Travel time savings to motorists who used the highway before the widening	836
(ii)	Travel time savings to new motorists (induced demand)	25
(iii)	Travel time losses due to construction	−35
(iv)	Reliability benefits	83
	Total travel time benefits after 6 years	909
(v)	Construction cost	1970
(vi)	Maintenance cost	250
	Total cost after 6 years	2220
	Total benefits minus costs after 6 years	−1311

Notes: Net present value in mln euro is reported. Travel time savings and losses have been computed using the estimated coefficients from last section and a VOT of 20 euro/hour (Adler and van Ommeren, 2016). Reliability benefits are set to 10% of the travel time changes (based on Van der Loop et al., 2014). Construction costs (5 million euro per lane kilometre) are an average based on the cost estimates made by the Dutch Ministry of Infrastructure and Water Management for 110 km two-lane widenings that are planned for the coming years. Yearly maintenance costs are set to 2% of the construction cost, based on the rules of the Ministry.

have been ignored in the above welfare analysis, which was essentially based on a partial equilibrium assumption of a given spatial structure of economic activity, ignoring, for example, economic advantages related to agglomeration (Lucas and Rossi-Hansberg, 2002).

A priori, one expects that the effects of widenings on wider economic activity and spatial structure will be quite different from the effects of *greenfield* highways which have been studied intensively starting with the seminal papers by Baum-Snow (2007, 2010). In particular, as discussed in Section 1, one expects these effects to be much smaller, and to occur mainly locally. We emphasise here that the widenings in our data are mainly situated *between* large economic centres and not *within* large economic centres. In such a setting, we expect *local* effects along highway segments that experienced widenings. People and firms might take advantage of the reductions in travel time and move to the locations near the widenings inducing local population and employment growth. This might reduce economic activity further away from widenings, particularly at competing locations that are relatively close, so changes in agglomeration may be expected to occur (Lucas and Rossi-Hansberg, 2002; Teulings et al., 2018). To verify this hypothesis, we aim to estimate the short-run effects of widenings on economic activity and spatial structure (employment, population, commercial floor space and residential floor space) at a low aggregation level (four-digit postcode areas which cover about one square kilometre, on average). To account for possible endogeneity, we exploit a similar strategy as in Section 4.

6.1. Empirical model and identification

We examine the effect of widenings on economic activity in the vicinity using annual information on employment, population, commercial floor space and residential floor space per four-digit postcode area. Postcode areas are small and part of larger regions. Hence, for each postcode area i, located in region j in year t we observe economic activity, denoted by Q_{ijt}. The changes in highway supply within vicinity of an area induced by widenings are captured by increases in lane kilometres within a given radius. Here, we will focus on changes within 10 km of the area.

To examine the effects of widenings in the year $t-L$ on economic activity in the year t, we use a dynamic specification similar to Equation (1):

$$Q_{ijt} = \sum_{L=-3}^{6} \alpha_L^0 H_{it-L}^{0-10} + \gamma_i + \tau_j t_t + \epsilon_{ijt}, \tag{6}$$

where H_{it-L}^{0-10} denotes the log of highway lane kilometres within 10 km and we let L vary from -3 until $+6$ years.[37] Q_{ijt} refers to the logarithm of employment, population, commercial and residential floor space, respectively, γ_i is the postcode fixed effect and $\tau_j t_t$ is a regional time trend. The error term is denoted by ϵ_{ijt}.

Additionally, we will distinguish between changes in lane kilometres within 5 km of the area, and further away—between 5 and 10 km. Hence, we also estimate:

$$Q_{ijt} = \sum_{L=-3}^{6} \alpha_L^1 H_{it-L}^{0-5} + \sum_{L=-3}^{6} \alpha_L^2 H_{it-L}^{5-10} + \gamma_i + \tau_j t_t + \epsilon_{ijt}, \tag{7}$$

where H_{it-L}^{0-5} and H_{it-L}^{5-10} denote the log of highway lane kilometres within 5 km and between 5 and 10 km, respectively.

We are mainly interested in the effects of α_L^i, $i=0, 1, 2$ for $L \geq 0$. We concentrate here on the cumulative effect 6 years after the widening, $\sum_{L=0}^{6} \alpha_L^i$, and the effect in the 3 years before the widening to test for the presence of pre-trends.[38]

To account for possible endogeneity, we follow a similar strategy as in Section 4. First of all we include postcode fixed effects γ_i to control for time-invariant unobservables. Further, we focus only on those locations that experienced a widening in their proximity (within 10 km). This relaxes the identifying assumption for causal inference as it only requires that, conditional on the widening, the exact timing of the widening is exogenous, that is, not correlated with ϵ_{ijt}. As explained in Section 2, this assumption arguably holds

37 As an alternative, one may use residential and firm market access, as used, for example, in Tsivanidis (2022), which can speak to the welfare implications more directly. The main advantage of our approach is that we do not have to specify the travel time gains between locations (which differ from the travel time gains measured by us for regions), the size of the geographical market as well as the distance decay within this market. Consequently, we impose less structure on the data.

38 The coefficients for 3 years before are reported in Supplementary Appendix H, together with the full estimates.

in the Dutch institutional setting because precisely timing the widenings is not feasible. Although governments may be aware at which locations the economy will grow, and may even plan the building of certain housing stock or commercial space there, the exact year of widening is impossible to control so it can be considered as good as random. Still, we take another step to deal with the possible threat that widenings may occur at locations where governments expect changes in economic growth. In the regression analyses, we include as additional control a *region-specific* time trend $\tau_j t_t$, where a region contains, on average, three postcodes. This variable is important as it controls for spatial trends at a low level of aggregation and thus accounts for possible continuous shifts in local transportation demand.

Another possible concern is the presence of alternative policies that came into effect during our sample period, or other confounding factors. Because in our data there are more than 30 widenings, varying considerably in terms of the opening year and the geographical location, it is very unlikely that all the widenings were in the same way affected by the same confounding variable.

6.2. Data on economic activity

To estimate the effect of widenings on broader economic activity, we use a range of annual data from different sources all available per (four-digit) postcode area for the period 2000–2011. These areas are quite small and cover, on average, approximately 1 square kilometre.[39] Economic activity data include *employment* (provided by LISA – Landelijk Informatiesysteem van Arbeidsplaatsen (Nationwide Information System of Jobs)) and *population* (provided by Statistics Netherlands). We also have information on *commercial floor space* and *residential floor space*. This is derived from BAG – Basisregistratie Adressen en Gebouwen (Key Register of Addresses and Buildings) – provided by the Netherlands' Cadastre Land Registry. We restrict our analysis to areas within 4 km of a highway ramp (we also experimented with other distances).

Table 7 reports descriptive statistics of the sample. We focus on the period between 2000 and 2011. During this period, areas in question observed an increase of about 15% additional lane kilometres within a radius of 5 km and 10% within a radius of 5–10 km, due to widenings. It is further noted that employment, measured in number of employees, as well as commercial floor space, measured in square metres, experienced a much stronger increase than population and residential floor space.

6.3. Results

We now discuss the effects of widenings on economic activity. Tables 8 and 9 summarise the estimates of Equations (6) and (7), showing the accumulated effects 6 years after the widening. Supplementary Appendix H reports the complete estimation results, including those for the 3 years before. It appears that there are no statistically significant trends in economic activity before the widening, supporting the underlying assumption of no trends.

Our results imply that, after a widening, there is no statistically significant overall effect on economic activity within a 10-km radius of the highway. In contrast, we document a positive highway lane supply elasticity of employment and commercial real estate within

39 A four-digit postcode area contains about 2000 dwellings.

Table 7. Descriptive statistics economic activity, 2000–2011

	Employment, commercial floor space				Population, residential floor space			
	2000		2011		2000		2011	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Lane kms 0–5 km	77.35	(40.90)	89.84	(44.22)	74.71	(40.44)	86.91	(43.85)
Lane kms 5–10 km	161.35	(81.58)	178.74	(86.77)	155.60	(81.00)	172.58	(86.45)
Lane kms 0–10 km	238.70	(110.03)	268.57	(115.80)	230.30	(109.79)	259.47	(116.36)
People (×1000)	3.05	(3.85)	3.45	(4.27)	5.54	(4.39)	5.77	(4.48)
Floor space (m2 × 1000)	104.07	(147.45)	131.56	(189.44)	251.86	(190.45)	282.81	(210.46)
Number of postcodes	559		559		596		596	

Notes: We show means and standard deviations *per 4-digit postcode*—an area of around 1 by 1 kilometre with, on average, 2000 houses. Employment and population are measured in thousands of people. Floor space is measured in thousands of squared meter.

Table 8. Elasticity of employment and commercial floor space

Dependent	Log commercial floor			Log employment		
	0–10 km	0–5 km	5–10 km	0–10 km	0–5 km	5–10 km
6 years after	0.137	0.273*	−0.215	0.066	0.236**	−0.207
	(0.142)	(0.147)	(0.144)	(0.136)	(0.105)	(0.163)
Postcode FE	559	559		559	559	
Year FE	12	12		12	12	
Observations	6707	6707		6707	6707	
R^2 within	0.36	0.36		0.24	0.24	

Notes: The independent variable is log lane kilometres in a 0–5, 5–10 and 0–10 km buffers surrounding a postcode, per year. The columns 0–5 and 5–10 report the estimates from one and the same specification including both radiuses. Standard errors (clustered at postcode level) are in parentheses. *, ** and *** represent 10%, 5% and 1% significance, respectively.

Table 9. Elasticity of population and residential floor space

Dependent	Log residential floor			Log population		
	0–10 km	0–5 km	5–10 km	0–10 km	0–5 km	5–10 km
6 years after	0.081	−0.022	0.117	0.091	0.071	−0.007
	(0.071)	(0.071)	(0.118)	(0.112)	(0.189)	(0.205)
Postcode FE	596	596		596	596	
Year FE	12	12		12	12	
Observations	7130	7130		7130	7130	
R^2 within	0.31	0.31		0.18	0.18	

Notes: The independent variable is log lane kilometres in a 0–5, 5–10 and 0–10 km buffers surrounding a postcode, per year. The columns 0–5 and 5–10 report the estimates from one and the same specification including both radiuses. Standard errors (clustered at postcode level) are in parentheses. *, ** and *** represent 10%, 5% and 1% significance, respectively.

5 km and an opposite, negative, impact, with an elasticity of comparable size (in absolute value) at a further away distance. This strongly suggests that commercial space and employment relocate to the direct vicinity of the highway (0–5 km) from somewhat further away locations (5–10 km). Hence, this suggests a local relocation of employment to places with lower travel times and better accessibility.

Our results seem to differ from estimates obtained for greenfield highways. For example, Möller and Zierer (2018) find for Germany that a one-standard-deviation increase in the growth of autobahn length between 1937 and 1994 led to employment growth of between 2.7% and 3.4% in the region where the highways were realised. In contrast to their findings, we do not document any effect for regions of 10 km around the highway, but only evidence for substitution *within* the region. For population and housing, we do not find any statistically significant effects.

In summary, we do provide evidence that highway widenings restructure local employment, but we do not find any support for the claim of employment growth at a more aggregate level. We do not find any effects for population.

7. Conclusions

This article analyses the short-run effects of highway widenings—adding new lanes to existing corridors—on congestion and traffic demand. We document that in the Netherlands highway widenings take place on congested corridors and immediately and substantially reduce travel times both on the widened segment and in the wider region. The effect turns to be persistent up to 6 years after a widening and takes place despite the strong increase in travel demand which we also document. Widenings furthermore induce changes in trip scheduling, as the proportion of motorists travelling during the peak strongly increases. We provide evidence that the time saving benefits induced by widenings cover about 40% of the widenings' cost within 6 years.

Our article is the first to shed light on the short-run effects of the widenings and provides a possible explanation of why the widenings are a frequent policy measure chosen to deal with congestion. Our findings on the presence of short-run time saving benefits complement the literature by enriching the existing knowledge that documents the fundamental law of congestion for the long run (Duranton and Turner, 2011; Garcia-Lopez et al., 2021).

Our welfare analysis is based on the assumption that spatial restructuring of the economy due to widenings is minor, that is, agglomeration effects of widenings are small, hence the main welfare effects are through changes in travel demand and time savings. This assumption is supported by our data. We do not find any evidence that economic activity increases within 10 km of a widening. However, we provide evidence that highway widenings induce a local restructuring of economic activity: employment within 5 km of the highway rises, while employment further away, between 5 and 10 km, is reduced.

It is important to point out that our study focuses on widenings only, and our welfare results are unlikely to hold for greenfield highway construction. Widenings have two important characteristics which make them different from greenfield highway construction. First, the construction costs of widenings are much lower than of greenfield highways. Second, highway widenings are typically constructed to remove bottlenecks, which can be easily identified, and where latent demand is likely substantial. This makes it plausible that the return on investment of widenings that remove bottlenecks tends to be larger compared with greenfield construction where public authorities tend to have less information about latent demand.

Our results leave a number of research questions open. First, it is unclear whether the ‘fundamental law of congestion’ applies for widenings which we have studied for the Netherlands. We find that travel time gains do not disappear, and do not even trend down, during the 6 years we study. This allows for a possibility that the effects of widenings on travel time reductions do not fully disappear in the long run, implying that the long-run demand function is not perfectly elastic. Further research into the shape of the demand curves might improve our understanding of the applicability of the fundamental law to different countries. Another, related, question that our article did not give an answer to is the mechanisms and sources of car travel demand induced by widenings. Understanding any rescheduling new motorists may have undertaken (e.g. from other routes, time slots or transportation modes) would allow to get a better insight into how and why induced demand eliminates speed increases from a highway improvement.

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Supplementary material

Supplementary data for this article are available at *Journal of Economic Geography* online.

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