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The effect of wind turbines alongside motorways on drivers' behaviour

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This paper presents the results of a first study aimed at investigating whether the presence of wind turbines in close proximity to motorways leads to behavioural adaptations among passing drivers. Empirical data from loop detectors and temporary video cameras were analysed in a study employing a before-and-after design at a site near Rotterdam, The Netherlands. Analyses of driving speed and standard deviation of speed (corrected for trend effects through the use of control sites) were performed as well as analyses of the lateral position and standard deviation of the lateral position and an observation of serious traffic conflicts.

The results showed that constructing wind turbines alongside a motorway led to some clearly observable effects on drivers' behaviour. The analyses of the speed data showed that the mean speed was lowered by 2.24km/h (corrected for trend effects) after the construction of the wind turbines while the standard deviation of the speed significantly increased. After the construction of the wind turbines, drivers took a lateral position somewhat more to the left-hand side in their driving lane. There was an indication close to the 0.05 significance level (p=0.057) that the standard deviation of the lateral position slightly increased when the rotor blades were in

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transversal position. In the before period as well as in the after period, no serious traffic conflicts were registered.

The increase in standard deviation of speed and in lateral position are two factors that intrinsically can have an unfavourable effect on road safety. However, the observed order of magnitude of the change was shown to be quite limited. Earlier research suggests that negative effects on road safety are only expected for changes substantially greater than the ones that were observed in this study. On the other hand, there was a significant reduction in driving speed, which might have a favourable effect on the expected number and severity of crashes, although it could also be a compensatory mechanism that indirectly indicates a reduced driving performance. From these findings, it can be concluded that, based on the observed variables, no substantial negative effects for road safety were found in the present study. The authors recommend continuous monitoring and further research on the topic.

Keywords: *Wind turbines, Motorways, Behavioural observations, Lateral position, Speed, Road safety.*

1. Introduction

Wind power plays a significant role in the current conversion to renewable energy sources that can be observed in many countries (Pedersen et al., 2010). Wind turbines are devices that convert the kinetic energy from wind into electrical power. However, wind turbines are often opposed by the local community because they are considered to be a visual and acoustic annoyance (Breukers and Wolsink, 2007). On the other hand, more remote places with a low population density are not necessarily a better alternative, since they often constitute otherwise unspoiled landscapes with high values for recreation and tourism that could be diminished due to the construction of wind turbines (Pedersen et al., 2010). Additionally, such locations are quite uncommon in densely populated regions such as Western Europe.

The land adjacent to motorways seems to be a potentially desirable location to erect wind turbines. They often pass through less densely populated areas, and placing wind turbines near motorways avoids long and expensive connections to the existing power grid as well as the necessity to build additional access roads for construction and maintenance (Seifert et al., 2003). However, wind turbines are conspicuous objects in the landscape due to their size and the movement of the rotor blades. In that respect, the wind turbines might be a potential source of distraction for drivers when the wind turbines are positioned near roads, which could, in turn, lead to road safety issues.

The aim of this paper is to examine the effects of wind turbines in close proximity to motorways on observable road user behaviour. A better insight into the possible behavioural adaptations of drivers can contribute to assessing the possible safety effects of constructing wind turbines in close proximity to motorways. To this aim, analyses of driving speed and standard deviation of speed, analyses of the lateral position and standard deviation of the lateral position, and an observation of serious traffic conflicts are performed.

2. Background

2.1 The impact of roadside objects on drivers' behaviour

Drivers' distraction from the primary task of driving, and the role it plays in motor vehicle crashes, has been the subject of a great deal of research in recent years, and it has been shown to be a contributing factor in many crashes (Stavrinos et al., 2016). The importance of distraction as a contributory factor to crashes produces a variety of estimates depending on the criteria used to attribute distraction. Most estimations fall within the range of 25-50% (Recarte & Nunes, 2009).

Driver distraction is found to negatively affect driving performance, as measured by for instance higher levels of drivers having no hands on the steering wheel, their eyes directed inside rather than outside the vehicle, and their vehicles wandering in the driving lane or crossing into another lane (Stutts et al., 2005).

Research towards drivers' distraction has mostly focused on distraction as a result of in-vehicle distractors (e.g. mobile phone use, radio tuning, conversations with passengers,…) (Antonson et al., 2014). Distraction caused by aspects of the road environment is, however, an important issue as well (Horberry et al., 2006). Two American studies suggest that 29-35% of reported distractions in crashes relate to distractions outside the vehicle (Glaze & Ellis, 2003; Stutts et al., 2001). It is important to remember that these figures may underestimate the impact of external distraction, because the determination of contributing factors of fatal crashes relies on witness reports and/or a reconstruction of the crashes, which may fail to identify some of the contributing factors (Stavrinos et al., 2016). Stutts et al. (2005) also identified distractions outside the vehicle as one of the most common types of distraction during normal driving conditions.

Studies on specific features outside the vehicle that may cause driver distraction are few, studies about roadside billboards or other advertisements being an exception. A study by Antonson et al. (2014) found that drivers' behaviour was affected by objects in the landscape. Roadside objects close to the roadway caused a shift in lateral position towards the centre of the road. They also found an increase in the variability of lateral position when drivers pass a roadside object, especially when the object was located far away from the road.

The amount of visual information in road environments is generally increasing, which implies that the road environment is increasingly prone to producing information that may distract the driver (Horberry & Edquist, 2009).Visual clutter (objects not relevant to the driving task) in the road scene is likely to have negative safety implications (Horberry et al., 2006). Potentially risky situations can emerge in case irrelevant objects attract the attention of the drivers to such an extent that too little attention remains for the actual driving task (Schreuder, 1992).

In summary, research suggests that conspicuous features outside the car (such as roadside objects) can distract drivers, and may therefore lead to crashes (Antonson et al., 2014).

2.2 The impact of wind turbines near roads on passing drivers

The effect of wind turbines near roads on passing drivers is a topic that has been largely unexplored. One driving simulator study was found in which the effects of wind turbines on drivers were examined (Alferdinck et al., 2012). The study consisted of different scenarios of a motorway stretch in The Netherlands. Two conditions for the position of the wind turbines were included, one in which the wind turbines were positioned at 55 m from the pavement and one in which they were more closely located to the roadway at about 26 m from the pavement. The official guidelines in The Netherlands state that wind turbines are allowed at a distance of at least 30 m from the outer edge of the pavement, or in the case of a rotor diameter larger than 60 m, at a distance of at least half of the rotor diameter. The scenario with the wind turbines positioned at 55 m from the pavement is therefore in line with the official guidelines, whereas the scenario with the wind turbines positioned at 26 m is not. In locations near interchanges or in situations where the rotor blades would rotate above the pavement, wind turbines are allowed only when additional research shows that there will be no unacceptable increase in risks to road safety.

The primary goal of the study by Alferdinck et al. (2012) was to examine whether a planned stretch of wind turbines positioned more closely to the pavement than prescribed by the official guidelines would cause unacceptable risks to road safety. Two conditions for the rotor blades of the wind turbines were defined: one 'favourable condition' (rotor blades parallel to the roadway and with a slower rotation speed of 7.8 rpm) and one 'unfavourable condition' (rotor blades perpendicular to the direction of travel, which implies that they rotate partly above the pavement, with a higher rotation speed of 13.7 rpm).

The results of the study indicated that the standard deviation of driving speed (SDDS) is higher when the wind turbines are positioned at 26 m from the pavement instead of in line with the official guidelines. Also, the standard deviation of the lateral position (SDLP) is higher in the plan condition compared to that in the policy condition. In addition, it was found that participants gazed longer at the wind turbines when they were located at the planned locations compared to those at the official guideline locations. With the rotor blades in the unfavourable condition of being perpendicular to the road, the average speed was slightly lower than in the favourable condition. In the unfavourable condition, participants also gazed longer at the wind turbines than when they were in the favourable condition.

The authors concluded that the participants were more distracted by the wind turbines when these were positioned according to the project plan, compared to when they were positioned in line with the official guidelines. The found effects are statistically significant, but their order of magnitude is small. The authors therefore concluded that there are no indications of an unacceptable increase in a risk to road safety, and they gave a positive recommendation for the implementation of the project plan. Note that the study presented in this paper is a follow-up on the simulator study by Alferdinck et al. (2012) in which the revealed behaviour of drivers was explored using empirical data in a study with a before-and-after design.

3. Methodology

The possible effects of erecting wind turbines in close proximity to a motorway on drivers were analysed in an empirical before-and-after study design at a test location near Rotterdam, The Netherlands. Three types of analyses were performed:

- A before-after analysis of driving speed using data from loop detectors and controlled for confounding factors by the use of a control group;
- A before-after analysis of the lateral position of vehicles within their driving lane using video footage collected at the research location;
- An analysis of occurring traffic conflicts.

3.1 Research location

The research location was a section of motorway N15 near Rotterdam, The Netherlands. In 2014, a windfarm of eight wind turbines was constructed alongside the motorway. The wind turbines are of the horizontal axis type, and they have a hub height of 90 m and a rotor diameter of 110 m. The nacelle and rotor blades of the wind turbines are rotatable, and are pointed automatically facing into the wind for maximum operation efficiency. Due to space constraints, most of the wind turbines of this windfarm are placed approximately 26 m from the pavement (see Figure 1, red pins), which implies that, during some wind conditions, the rotor blades of the wind turbines rotate partly above the pavement. The research location was the same as the one that was simulated in the driving simulation study by Alferdinck et al. (2012) which has been described in section 2.2. The motorway has two driving lanes in each direction and a speed limit of 100 km/h. The south-eastern driving direction was observed for this study since this direction is closest to the wind turbines, and it was therefore judged to be the one where the drivers would be most sensitive to possible effects due to the presence of the wind turbines. A street view picture of the research location is shown in Figure 2.

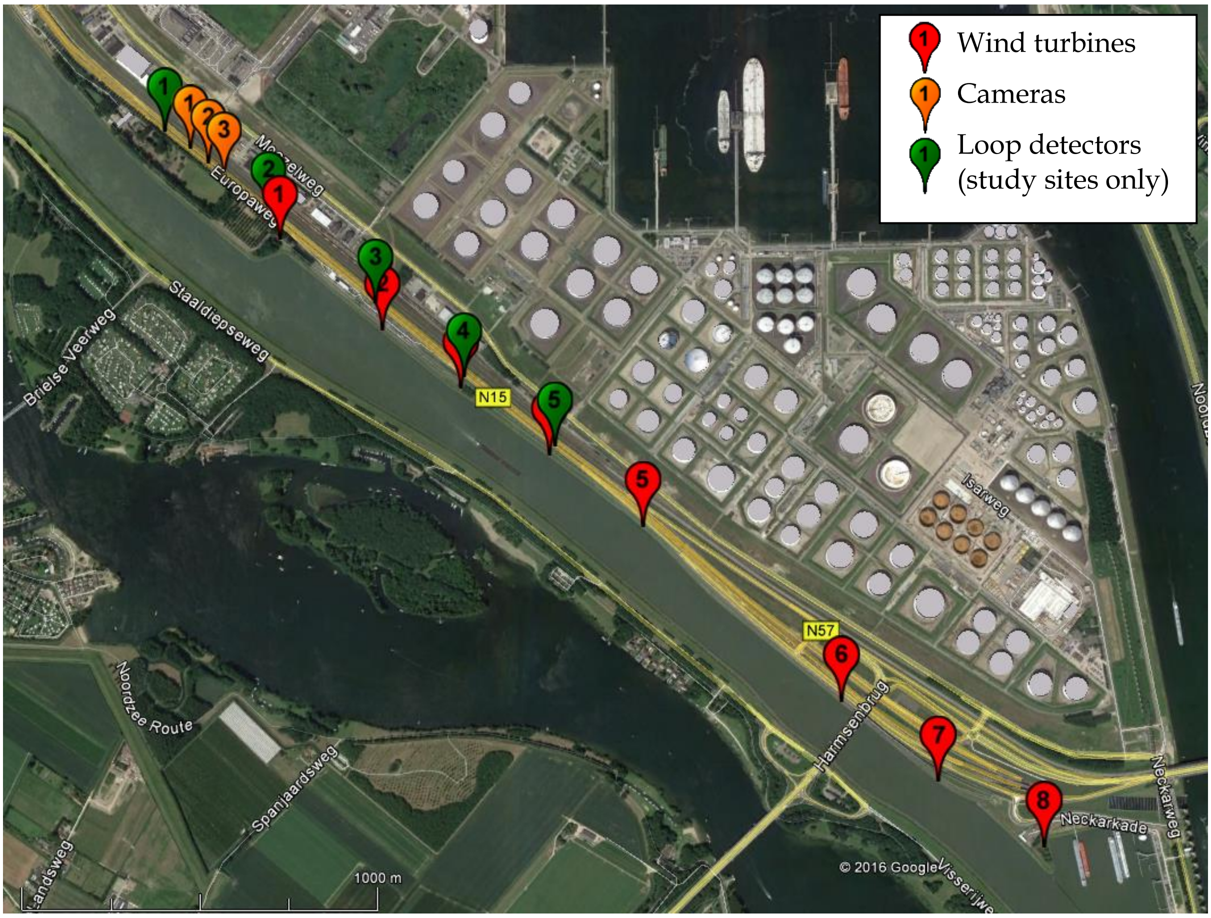

Figure 1. Research location. Positions of wind turbines, temporary cameras and loop detectors (study sites only) are indicated (image adopted from Google Earth).

Figure 2. Research location. Street view near camera 1 after construction of wind turbines (image adopted from Google Street View).

3.2 Analysis of drivers' speed

To gain a better insight into the possible effects of wind turbines on drivers' speed, two full months of speed data were analysed in the before period and in the after period. The before period was selected as October 1, 2013 through November 30, 2013, and the after period as February 1, 2015 through March 31, 2015. These periods were chosen to match the period of the video observations (see subsection 3.3). Speed data were obtained from the Dutch National Database of Road Traffic Data (Nationale Databank Wegverkeersgegevens) which stores data from inductive loops on the Dutch road network. In order to make the analyses as detailed as possible, the most disaggregated data available were used, which were speed data on the level of one minute per driving lane. Individual vehicle speeds were not available. Possible confounding factors such as seasonal effects and traffic volumes were controlled through the inclusion of control sites that were as similar to the treatment sites as possible except for the fact that they had not undergone the treatment that we were interested in evaluating, i.e., the construction of wind turbines alongside the road (Elvik, 2002).

We used the data of five consecutive loop detectors over a stretch of road of 1.5 km near the wind turbines (see Figure 1, green pins). The detectors were placed in the south-eastern driving direction, which was closest to the wind turbines. The first loop was located approximately 400 m before the first wind turbine, and the last loop was located further down the wind farm, close to the fourth wind turbine. In addition, two control sites had been selected: one downstream from the treatment sites and one upstream (control sites are not visible in Figure 1). Consequently, we were able to analyse speed data from five treatment locations and two control sites before and after the construction of the wind turbines. For each of these locations, we obtained on average 114,559 speed observations, ranging from 110,212 to 118,720, each observation being the average speed for one lane during one minute. Data were left out for minutes during which no vehicles passed. It should be mentioned that the pavement of the treatment sites was resurfaced between the before and after periods. One of the selected control sites underwent similar resurfacing work between the before and after period which enabled us to account for the possible effects of such work. The second control site did not experience any road works between the before and after period. No other control sites in the vicinity of the study sites could be included because of missing data for the before or after periods.

Preliminary analyses showed an overrepresentation of relatively low driving speeds (65–75 km/h) during night time, which appeared to be caused by occasional roadside maintenance works. To avoid possible biases because of this work, only data of the period 06:00–21:59 were used in the analyses of speed.

To estimate the change in mean speeds at treated locations, taking general trend effects into account, a linear regression model with normal distribution and identity link function was fitted using the SPSS GENLIN procedure. The model can be expressed as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 + \varepsilon , \quad (1)$$

where Y = average speed at a location in a certain period; X1 = location (treatment/control); X2 = period (before/after); β1 = difference in mean speed between the treated locations and the control sites; β2 = difference in mean speed between the before and after period; β3 = interaction effect, which indicates the difference in the mean speed between the before and the after period in the treated group, with control for other factors that had an influence on the driving speed through the use of the data of the control sites.

Weighted averages of the speed were used that took into account the number of vehicles that passed during each minute (procedure SCALEWEIGHT in SPSS). Histograms and normal probability plots show that the residuals of the mean speeds are approximately normally distributed. Differences of the standard deviations of the speeds between the before and the after period were assessed by means of Levene's tests.

3.3 Analysis of observed lane position

Video footage from temporary cameras was collected for the analyses of drivers' lane positions. The cameras were mounted on three consecutive lamp posts, covering a road segment of 200 m shortly before where the drivers arrived at the first wind turbine of the wind farm (see Figure 1, yellow pins). This segment was selected because we hypothesized that behavioural changes, if present, would be most plausible at this point because the visual impact of the wind turbines on the drivers would be strongest there. At this point, drivers would have approached the first turbine closely enough so that the turning rotor blades would be a very prominent element in their field of view, but not so close that the view of the rotor blades would be occluded by the top of their windscreen. Three conditions were measured: no wind turbines (before period), wind turbines parallel to the roadway and wind turbines perpendicular to the roadway. Both conditions of the after period are shown in Figure 3. Note that these are shots taken from an overview camera that was installed for the sole purpose of monitoring the status of the wind turbines; the cameras that were used for the analyses of lane position and traffic conflicts were tilted more downwards, which allowed for more accurate measurements.

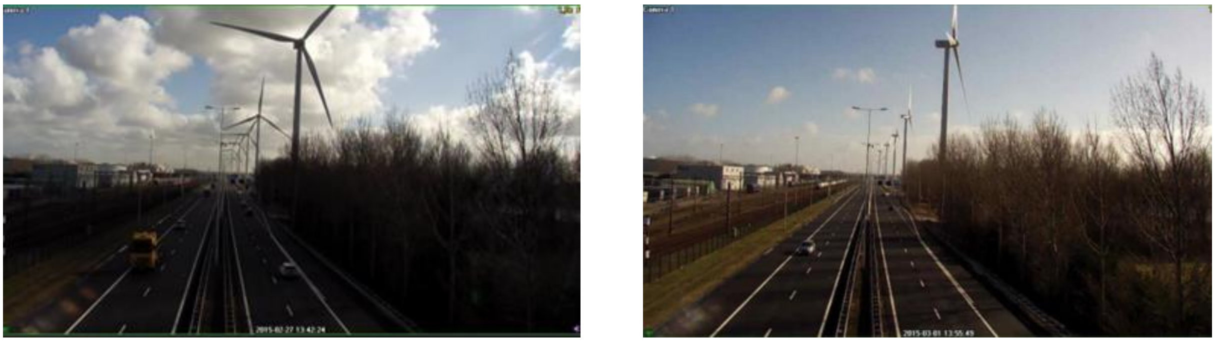

Figure 3. View of the project site with wind turbines in perpendicular condition (left) and parallel condition (right).

Video footage was collected during one week in the before period (early November 2013) and during 3.5 weeks in the after period (February–March 2015). More video footage of the after period was collected in order to ensure that a sufficient amount of video footage would be available for both conditions (rotor blades parallel to the roadway and perpendicular to the roadway). A total of 24 h was selected from the before period and 24 h from the after period (12 h with rotor blades in perpendicular condition and 12 h with rotor blades in parallel condition). Eighteen h from both the before and the after period were selected during daylight (8 h – 17 h) and 6 h were selected during night time.

Wind direction data for the study site were retrieved from the Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut) on an hourly basis. When the wind either blows from the ESE-SE (129°) or from the WNW-NW (309°), the wind turbines are perfectly perpendicular to the roadway. Wind directions deviating less than 20° from these ideal positions are considered appropriate to include in the perpendicular condition. A similar approach was applied to preselect potential hours for the parallel condition. Only hours without precipitation were selected, and only with an average hourly wind speed between 6 km/h and 38 km/h (2–5 Beaufort). These wind speeds were considered sufficiently strong to make the rotor blades rotate enough to be conspicuous, but not so strong as to have an effect on driver behaviour (e.g., vehicle instability due to gusts of wind).

For the final selection, first the hours with wind turbines in perpendicular position were chosen, since these were the least common. Based on these hours, matching hours were selected for the before period and for the parallel condition. These hours were selected so that the traffic volumes between the different conditions were as similar as possible. Nearly all matched hours differed less than 10% from each other regarding traffic volume.

Videos were analysed using T-Analyst, a semi-automated video analysis tool developed at Lund University, Sweden (Lund University, Transport and Roads, 2015). The software was calibrated to transform the image coordinates of each individual pixel to road plane coordinates, which allows to accurately determine the position of an object (Laureshyn et al., 2017). This way, the lateral position of vehicles within the lane could be measured.

The lateral position of every tenth passing vehicle was measured at three measurement points (one per camera). The lateral positions were measured immediately after the vehicle entered the view of the camera because the measurement accuracy is highest closest to the camera. Since the cameras were set up in the median of the road, the left-hand side of the vehicles was the most visible to camera. Therefore, the lateral distances were measured from the left-hand side of the vehicle (outermost contact point of the tire on the pavement) and the inside (right-hand side) of the pavement marking left of the vehicle. In cases where the vehicle was driving in the right-hand lane, the distance was therefore measured to the centre line. In cases where the vehicle was driving in the left-hand lane, the distance was measured to the left edge line. For each vehicle, the standard deviation of the three lateral positions was calculated as well. The standard deviation of lateral position indicates the degree of swerving of the vehicle.

Apart from the lateral position, a number of other elements were registered that could have had an effect on the lateral position of the vehicle as well. These elements were the lane that the vehicle was driving in (left or right), the vehicle type (heavy goods vehicle [HGV], minivan, passenger car) and whether it was day or night.

It should be mentioned that there was an exit toward a petrol station shortly downstream of the study section that had been slightly extended during the resurfacing works that took place on the motorway between the before and after period. It was therefore decided to omit all vehicles that took this exit to the petrol station as well as any vehicles driving immediately in front or behind a vehicle taking the exit to avoid any possible biases due to this change. In addition to these vehicles, vehicles that switched lanes within the observed road section were omitted from the analyses because their choice of lateral position was mainly the consequence of their decision to switch lanes.

Similar to what was done in the analyses of driving speed, two linear regression models were built. The first model investigated which elements had an impact on the lateral position of the driver in absolute terms (the mean of the three measurement points was the dependent variable). The second regression model investigated which elements affected the standard deviation of the three measured lateral positions, which was an indicator of how much the vehicles weaved.

3.4 Analysis of traffic conflicts

Traffic conflicts, sometimes referred to as "near-accidents", are defined as observable situations in which two or more road users approach each other in space and time to such an extent that a collision is imminent if their movements remain unchanged (Svensson and Hydén, 2006). Research has shown that there are strong correlations between serious traffic conflicts and traffic crashes; they appear to belong to the same process, only with a different degree of severity (Hydén, 1987). The occurrence of traffic conflicts is therefore a strong indicator of a risk of traffic crashes.

Various traffic conflict indicators can be used to detect traffic conflicts. In this study, situations were considered serious traffic conflicts if they fulfilled one of the following criteria:

- They were considered to be a serious traffic conflict according to the Swedish Traffic Conflict Technique (STCT) (Hydén, 1987). Based on driving speed and the distance to the projected (imaginary) collision point, the so-called time-to-accident (TA) value can be calculated. Based on the TA-value, it can be decided whether a traffic conflict is serious or not. The STCT defines a threshold value to distinguish between serious and non-serious TA-values that depends on the driving speed.

- They had a minimal time-to-collision (TTCmin) value lower than 1.5 s. The time-to-collision is the time remaining before a potential collision if direction and speed are unchanged. Research has shown that such values rarely happen in normal traffic interactions (van der Horst, 1990).

For the traffic conflict observations, the same 48 h of video footage were used as in the analyses of the lateral position of vehicles. First, all interactions that seemed dangerous were manually preselected by the observer. Next, T-Analyst was used to accurately measure the severity of the situation and to decide whether it was a serious traffic conflict or not.

4. Results

4.1 Analyses of drivers' speed

The results of the analyses of drivers' mean speed are shown in Table 1. Overall, the mean speed was 2.24 km/h lower in the after period compared to the before period. This was the result of an observed reduction in mean speed of 0.44–1.75 km/h at the study sites, combined with an increase in mean speed of 1.23–2.29 km/h at the control sites. There seemed to be a tendency that the difference in mean speed between the before and after period gradually increased when the driver got further into the wind farm.

Also, the results of the analyses of the standard deviation of driving speed (SDDS) at each site are shown in Table 1. An increase in the SDDS was observed at each study site. Levene's tests for homogeneity of variance showed that these increases were all statistically significant. The greatest increase in the SDDS was observed at the first study site, while the increase in SDDS gradually lessened towards the last study site. On the other hand, the control sites either showed a negligible difference (control site upstream) or even a reduction in the standard deviation of speed (control site downstream).

4.2 Analyses of observed lateral position

In total, the lateral positions of 3,649 vehicles were analysed (1,879 in the before period, 882 in the after period with rotor blades in parallel condition and 888 in the after period with rotor blades in perpendicular condition). The results of the regression model for the lateral position are shown in Table 2. Recall that measurements were taken from the left-hand side of the lane. This means that estimates with a *positive* sign indicate a lateral position *closer to the right-hand side of the lane*, while *negative* estimates indicate a position *closer to the left-hand side of the lane*.

All collected variables had a statistically significant effect on the lateral position. Vehicle type had a significant effect on the lateral position; HGVs drove closest to the left-side markings, followed by minivans, and passenger cars were positioned the farthest away from the left-side markings. This is quite straightforward, since HGVs are the widest vehicles and are therefore by definition closer to the pavement markings on both sides. It can also be seen that drivers in the left-hand lane were generally positioned closer to the left-side marking. Most probably, this resulted from the fact that most drivers in the left-hand lane were overtaking a vehicle in the right-hand lane and that they wished to keep a somewhat wider lateral distance from this vehicle by positioning themselves farther to the left of their driving lane. Drivers generally drove more closely to the left-hand markings during the night than during daytime.

Table 1. Differences in mean speed and SDDS between the before and after period.

			Overall effect					
			-2.24 km/h [-2.25; -2.24][1]					
Location	**No. of observations before** (= minutes and lanes with vehicle flow > 0)	**No. of observations after** (= minutes and lanes with vehicle flow > 0)	**Mean speed before (km/h)**	**Mean speed after (km/h)**	**Evolution before-after (km/h) [95%CI]**	**SDDS before (km/h)**	**SDDS after (km/h)**	**Evolution of SDDS (km/h)**
Study site 1	117,695	118,720	99.75	99.31	-0.44 [-0.44; -0.44]	9.24	10.57	+1.33
Study site 2	115,636	118,011	99.70	98.65	-1.05 [-1.06; -1.05]	9.70	10.67	+0.97
Study site 3	115,392	116,407	99.58	98.78	-0.79 [-0.80; -0.79]	9.45	10.33	+0.88
Study site 4	114,342	114,352	100.11	98.36	-1.75 [-1.75; -1.74]	9.67	10.29	+0.62
Study site 5	112,090	113,732	98.99	97.39	-1.60 [-1.61; -1.60]	9.86	10.07	+0.21
Control site 1 (upstream)	110,759	115,054	95.36	96.59	+1.23 [+1.23; +1.24]	7.67	7.69	+0.02
Control site 2 (downstream)	111,427	110,212	107.85	110.51	+2.29 [+2.28; +2.29]	11.09	9.90	-1.19

[1] Parameter estimates for β_3 in Eq. 1 with 95% CI.

The previous variables are mainly included in the model to correct for any possible confounding effects on the lateral position in order to be able to investigate the pure effect of the condition of the wind turbines, which is our main interest here. It appears that in both conditions of the after period, vehicles were positioned closer to the left-hand side of the driving lane. The results show that this tendency to drive closer to the left-hand side of the lane was more pronounced in the condition with the blades parallel to the roadway than in the condition with the blades perpendicular to the roadway. The mean lateral position indicated a shift of 13.6 cm to the left-hand side of the lane when the rotor blades were parallel to the roadway compared to the condition without wind turbines. In the condition with rotor blades perpendicular to the roadway, the lateral position showed a shift of 7.8 cm to the left compared to the condition without wind turbines.

Table 2. Regression model lateral position.

Variable	*p*-value of variable	Category	Estimate	S.E.	*p*-value of category
Constant	< 0.001		0.847	0.008	< 0.001
Vehicle type	< 0.001	HGV	-0.165	0.008	< 0.001
		Minivan	-0.045	0.015	0.003
		Passenger car	0 (ref.)		
Lane	< 0.001	Left	-0.156	0.009	< 0.001
		Right	0 (ref.)		
Time	< 0.001	Night	-0.066	0.015	< 0.001
		Day	0 (ref.)		
Condition	< 0.001	Blades parallel (after)	-0.136	0.009	< 0.001
		Blades perpendicular (after)	-0.078	0.009	< 0.001
		No turbines (before)	0 (ref.)		

Following the finding that drivers in the after period tended to choose a lateral position more to the left-hand side of their driving lane, a hypothesis could be that they also more often tend to drive in the left-hand lane instead of the right. Therefore, a χ^2-test was performed to see if there was a correlation between the driving lane and the condition of the wind turbine. The null hypothesis was that there would be no correlation between both variables. The test showed that this null hypothesis could not be rejected at the 95% confidence interval, $\chi^2(2) = 1.092$; $p = 0.579$. Also, in the case where the comparison was made between the before and after periods (hence merging both rotor blade conditions into one category), the null hypothesis could not be rejected, $\chi^2(1) = 0.326$; $p = 0.568$. This indicates that the presence of the wind turbines had no effect on the choice of driving lane.

Table 3 shows the results of the regression model for the SDLP. Vehicle type has a significant influence on the SDLP. There was no significant difference between passenger cars and minivans, but HGVs showed a significantly lower SDLP than both other categories. Most likely, this was caused by the fact that HGVs are less agile vehicles than minivans and passenger cars and because of the fact that HGVs' larger width allows for less lateral displacement than that of the other two types of vehicles. Vehicles in the left-hand lane showed a significantly lower SDLP than vehicles in the right-hand lane, and the SDLP was higher during daytime than during the night.

It needs to be noted that the condition of the wind turbines was again the main independent variable of interest. It can be seen that the variable "condition" was not statistically significant in the model. If we focus closely on the individual categories, it can however be observed that the difference between the "no turbines" condition and the "blades perpendicular" condition was very close to the level of 0.05 significance ($p=0.057$), which can be seen as an indication of a possible effect. It should also be mentioned that the order of magnitude of the effect was limited.

Table 3. Regression model standard deviation of lateral position.

Variable	*p*-value of variable	Category	Estimate	S.E.	*p*-value of category
Constant	< 0.001		0.141	0.003	<0.001
Vehicle type	< 0.001	HGV	-0.027	0.003	<0.001
		Minivan	-0.003	0.006	0.609
		Passenger car	0 (ref.)		
Lane	< 0.001	Left	-0.020	0.004	<0.001
		Right	0 (ref.)		
Time	0.011	Night	-0.015	0.006	0.011
		Day	0 (ref.)		
Condition	0.156	Blades parallel (after)	0.001	0.004	0.736
		Blades perpendicular (after)	0.007	0.004	0.057
		No turbines (before)	0 (ref.)		

4.3 Analyses of traffic conflicts

For both the before and after period, only a few situations were preselected by the observer for detailed measurement. Generally, very few dangerous situations took place. The few noteworthy situations that did take place were mainly situations where a vehicle changed lanes, impeding the path of an approaching vehicle in that lane. Further measurements of these preselected situations showed, however, that none satisfied the criteria to be considered a serious traffic conflict. Hence, no serious traffic conflicts were found in the before situation or in the after situation.

5. Discussion

5.1 Impact on driving speed

The analyses showed that the mean driving speed at the study sites decreased between the before and after periods, while the mean speed at the control sites increased during the same time periods. It was concluded that the mean speed decreased by 2.24 km/h as a consequence of constructing the wind turbines. This indicates a substantially stronger effect than that found by Alferdinck et al. (2012), who only found a slightly lower (0.4km/h) driving speed with rotor blades in the unfavourable (perpendicular) position compared to the favourable (parallel) condition, but found no effect caused by the position of the wind turbines themselves (26 m from the roadside in the project plan condition compared to 55 m in the official guidelines condition). The cause of the reduction in driving speed cannot be proven by the data analysed, but may be the result of distraction of the drivers because of the presence of the wind turbines.

Driving speed is an important factor in road safety; it strongly affects the risk of being involved in a crash as well as the severity of crashes (Aarts and van Schagen, 2006; Elvik et al., 2004). The relationship between changes in mean driving speed and their effect on traffic crashes is frequently expressed as an exponential function, also known as the Power Model (Elvik, 2009, 2013; Elvik et al., 2004; Nilsson, 2004). Using the exponents found by Elvik (2009) that apply specifically to motorways, the observed reduction in mean speed of 2.24 km/h is estimated to lead to a reduction in injury crashes by 3.6% and a reduction in fatal crashes by 8.9%. Everything else being equal, the effect of the found reduction in mean speed on traffic safety would therefore be positive, with a considerable decrease in especially the most severe crashes.

On the other hand, it should be kept in mind that a lower driving speed might be a compensatory mechanism of drivers to increase their margin for error when they are distracted (Horberry et al., 2006). In that respect, it could also be an indirect indicator of a reduced driving performance as a result of being distracted. Additionally, the reduction of the speed seems to be a local effect only that is not sustained over a longer distance, since the downstream control site does not show a lower mean speed after the construction of the wind turbines. On the contrary, the mean speed is even significantly higher at this control site, although it is unsure whether this could be a (negative) spillover effect that is attributable to the wind turbines.

The SDDS increased significantly between the before and after periods, ranging from +0.21km/h to +1.31km/h, while the SDDS did not change substantially or even decreased at the control sites. This indicated an increase in the heterogeneity of driving speed in the traffic flow. Comparable effects were found in the simulator study by Alferdinck et al. (2012). They found an increase of the SDDS by 0.41 km/h when the wind turbines were positioned according to the project plan condition compared to the official guidelines condition, and an increase in the SDDS by 0.3km/h in the perpendicular condition of the rotor blades compared to the parallel condition.

An increase in the differences in speed between vehicles generally tends to have a negative effect on road safety (Aarts and van Schagen, 2006). Detailed empirical analyses by Salusjärvi (1990), however, suggest that increases in the SDDS up to 2km/h do not have an effect on the risk of traffic crashes. The found effects on SDDS in this study were well below this threshold value. Therefore, it can be concluded that the small increase in the SDDS that was found would be unlikely to have a substantial effect on road safety.

5.2 Impact on lateral position

The analyses showed that the presence of the wind turbines had a significant impact on the lateral position of vehicles. In the after period, when wind turbines were present alongside the right-hand side of the roadway, it was observed that drivers drove more to the left within their driving lane. This could be an indication that drivers noticed the wind turbines and had a conscious or unconscious tendency to take a position on the road farther away from the wind turbines. This finding is in line with Antonson et al. (2014), who found that roadside objects close to the roadway lead to a lateral shift towards the middle of the roadway. The presence of the wind turbines did not, however, affect the drivers' lane choice.

Dutch traffic rules stipulate that drivers are, in general, obliged to stay as far to the right-hand side as possible ("keep right unless to overtake"). This rule is similar in most right-hand traffic countries that do not apply the "keep your lane" principle. Since the presence of wind turbines seems to lead drivers to position themselves more to the left-hand side of the lane, this principle is somewhat undermined by the presence of wind turbines. However, to the best of our knowledge, there is no research that suggests that a shift in the (mean) lateral position, as such, has a direct negative impact on road safety. The shift in lateral position does, however, suggest that the presence of the wind turbines could possibly have a distracting effect on some drivers. This increased distraction might have negative effects on road safety as demonstrated by Dingus et al. (2016).

However, it is remarkable that the tendency of drivers to take a position closer to the left-hand side of the lane was more pronounced when the rotor blades were in parallel position compared to the perpendicular condition. Our initial hypothesis was that the effect on the lateral position, if present, would be strongest with the rotor blades in the perpendicular condition because the rotor blades would be more conspicuous to the drivers in that condition. The reason for this finding remains uncertain.

The lack of a harmonised horizontal position of a vehicle within the driving lane is one of the primary factors in single-vehicle run-off the road crashes and of head-on crashes on undivided two directional roadways (Rosey et al., 2008). SDLP is often used as an indicator for lateral trajectory control. A higher SDLP, indicating a higher amount of "weaving" by the driver, is considered to be unfavourable for road safety (Helland et al., 2013; Verster and Roth, 2011). The analyses of the SDLP in our study showed an indication very close to the level of 0.05 significance ($p=0.057$) of a limited increase in the SDLP in the condition with rotor blades perpendicular to the roadway, compared to the condition without wind turbines.

Brookhuis et al. (2003) have formulated threshold values for SDLP. According to the authors, the SDLP should be lower than 0.25 m, and the relative change between the two conditions should be maximally 0.04 m. It is somewhat uncertain whether these values should be directly transferred as reference points for our study, since these values were based on a very large number of measurement points over an entire route, while our values were calculated using only three measurement points over a short road section. It is, however, clear that the values found in this study (on average 0.123 m and 0.129 m for the condition without wind turbines and the condition with rotor blades in perpendicular condition, respectively) were well below these threshold values, both in terms of absolute values and relative change. It can be concluded that it is unlikely that this minor increase in SDLP represents an increase in the risk of traffic crashes.

The simulator study by Alferdinck et al. (2012) found an increase in SDLP in the condition with wind turbines in the project plan position compared to the position according to official guidelines condition. The effects found in the study stayed within the limits defined by Brookhuis et al. (2003) as well. Since our own observational study did not have a condition with wind turbines positioned according to the official guidelines, a direct comparison of the results of both studies was not possible. Generally, however, both studies suggest a limited increase in the SDLP, which is not thought to lead to an increase in risk.

5.3 Impact on traffic conflicts

The fact that no serious traffic conflicts have been registered after the construction of the wind turbines can be seen as a positive indication from the perspective of traffic safety. It suggests that the presence of wind turbines does not directly lead to unexpected and very dangerous traffic interactions.

However, it should be emphasized that both the duration of the traffic conflict observations (2 x 24 h) and the length of the observed road stretch (200 m) were fairly limited. On road sections, traffic conflicts tend to be very dispersed, as opposed to intersections where they are strongly concentrated due to the large number of crossing and merging movements. Moreover, the complexity of a straight section of a motorway is quite low. Therefore, it would have been surprising if a high number of traffic conflicts had been observed.

5.4 Strengths, limitations and further research

A strength of the study is the fact that it is one of the first studies to analyse the effects of wind turbines alongside roads on drivers and on road safety. Since the roadsides of motorways can be desirable locations to erect wind turbines from an economic perspective and from the perspective of public acceptance, the results can be relevant for policymakers in the fields of traffic safety and sustainable energy.

A limitation of the study is the fact that only one study location could be observed. While there are no indications that the effects of wind turbines on drivers would be different at other locations, this still implies that generalization of the results cannot be guaranteed. This study should be seen as a first study on the subject that provides some first indications and raises some points for discussion that should be further investigated in future research.

An additional limitation is the fact that some minor adaptations were made to the infrastructure between the before and after period. While we do not immediately expect an influence of these minor adaptations on drivers' behaviour and measures were taken to avoid and/or account for possible adaptations, it cannot be completely excluded that these adaptations may have had an effect on the measurements.

This study focused on the possible effect of directly perceiving the wind turbines as objects alongside the motorway. An additional element that could play a role is the cast shade on the pavement caused by the moving rotor blades during sunny days. This aspect is beyond the scope of this study, and it should be further investigated in future research.

A strength of the study is the use of empirical (observed) data. This is beneficial for the validity of the research results because there should not be any doubt about whether the registered behaviours will take place in practice, as opposed to, for example, driving simulator data or survey data (De Ceunynck et al., 2015). An additional strength is the large sample sizes used for the analyses of speed and lateral position, which makes these analyses and the conclusions drawn from them quite robust.

A final strength is that the results from this study and the driving simulator study by Alferdinck et al. (2012) complement and strengthen each other. Earlier research has demonstrated the benefits of combining the results from a driving simulator study with the results from site-based observations (Polders et al., 2015). By combining the results of both studies, a more holistic view of the effects of wind turbines on drivers' behaviour and road safety is obtained.

5.5 Policy recommendations

Increases in standard deviation of driving speed (SDDS) and SDLP are two factors that could have a negative effect on road safety. The observed order of magnitude of the changes in our study, however, was limited, and earlier research suggests that, for both indicators, negative effects on road safety are only expected as a result of changes substantially greater than the ones that were observed in this study. On the other hand, our study showed a significant reduction in mean driving speed, which might have a positive effect on the expected number and severity of crashes, although it could also be a compensatory mechanism that indirectly indicates a reduced driving performance.

No substantial negative effects for road safety were therefore found due to the presence of wind turbines. Nevertheless, both this study and an earlier driving simulator study on the topic found some clear effects of the presence of wind turbines alongside the motorway on drivers' behaviour, which could indicate an increased amount of distraction. Reasoning from the cautionary principle, it might be advised to maintain adequate regulatory distances between pavement and turbines wherever possible, and not to position wind turbines close to locations that require an increased attention from drivers, such as motorway interchanges or road segments that are sensitive to traffic jams. Continuous monitoring and further research on the topic are recommended.

6. Conclusions

The conclusion of this study is that the presence of wind turbines alongside the investigated motorway stretch leads to observable behavioural adaptation effects among passing drivers.

Drivers drove significantly slower (-2.24 km/h) than before the construction of wind turbines. However, the SDDS across drivers increased. Drivers chose a lateral position more closely to the left-hand side of their driving lane when wind turbines were present. There was some indication of a limited increase in the SDLP in the condition with rotor blades in perpendicular position compared to the condition with no wind turbines, while no effects on the number of traffic conflicts were found.

The increase in SDDS and SDLP are two effects that intrinsically could have an unfavourable effect on road safety. However, the observed order of magnitude of the change is limited, and earlier research suggests that negative effects on road safety are only expected at changes substantially greater than the ones that were observed in this study. On the other hand, there is a significant reduction in driving speed, which might have a favourable effect on the expected number and severity of crashes, although it could also be a compensatory mechanism that indirectly indicates a reduced driving performance. From these findings, it can be concluded that, based on the observed variables, no substantial negative effects for road safety were found in the present case. The authors recommend continuous monitoring and further research on the topic.

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