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Empirical Speed Behavior on Horizontal Ramp Curves in Interchanges in the Netherlands

Haneen Farah, Aries van Beinum, and Winnie Daamen

Several studies in the literature have indicated that interchanges are the most crash-prone areas within the motorway system in number and severity of accidents. The reason is the high level of turbulence as a result of vehicle lane changes and speed variability. To understand the safety consequences of an interchange design (e.g., type of connecting ramps, radii and superelevation of curves, and lane and shoulder widths), an in-depth investigation of driving speed behavior is needed. Such an investigation requires the collection of detailed trajectory data on vehicles on different interchanges. These types of data are rarely available, and as a result, such studies are scarce in the literature. The main objective of this present study was to analyze driver speed behavior on different ramps at interchanges, and to develop an operating speed prediction model as a function of the road design elements. Trajectory data on free-moving vehicles were derived from stabilized video images taken from a camera mounted underneath a helicopter, which hovered over the road areas studied. Data were collected from 29 curves at six freeway–freeway interchanges in the Netherlands. The sample included nine direct connections, 12 semidirect connections, and eight indirect connections. The findings showed that speeds were affected by several road geometric characteristics of the curves, by driver expectancy and design consistency, and by the percentage of trucks in traffic. The operating speed prediction models developed in the study will provide designers with tools to estimate the operating speed during the design process.

An interchange is defined as "a system of interconnecting roadways in conjunction with one or more grade separations that provides for the movement of traffic between two or more roadways or highways on different levels" (*1*). Interchanges accommodate high volumes of traffic safely and efficiently compared with at-level intersections. There are many types of interchanges, which differ by size, number of levels, shape, cost, and scope. However, some of the most well-known types include the cloverleaf interchange, star, and turbine.

The type of ramp in place is one of the most significant ways in which these interchanges operate differently with respect to driving speed and the traffic flow that they can handle. Although in a cloverleaf ramps consist of loops with relatively tight curves and low design speeds, turbines have semidirect connections, and star interchanges have direct connections, which allow larger curve radii that can lead to higher operating speeds. In the Netherlands, the design speeds applied on ramps range from 50 km/h for indirect connections to 120 km/h on the widest direct connections. The type of connection (e.g., direct, semidirect, and indirect) and the design speed depend largely on a connection's function in the network and on traffic flow.

In the United States, McCartt et al. reported that 18% of all Interstate freeway accidents, 17% of injury accidents, and 11% of fatal accidents occurred at interchanges, although such locations constituted less than an estimated 5% of total freeway mileage (*2*). Given the significant percentage of accidents on interchanges, it is essential to understand how the geometric design of different interchanges, and more specifically the design of ramps, affects driver speed behavior. To obtain this understanding requires the collection of detailed trajectory data on vehicles on various interchanges and the road design characteristics. These types of data can provide insights into when drivers start to decelerate to adapt their speeds, how much they decelerate, and how the road design affects their speed profiles. High driving speeds and large variability in speeds were shown in earlier studies to affect the probability and severity of accidents (*3–5*).

The literature contains few studies that analyzed driving behavior at interchanges on the basis of trajectory data collected in the field (*2*). Most state-of-the-art studies can be categorized as crash analyses and studies that developed crash prediction models as a function of the types and characteristics of interchanges (*6–11*), studies that used driving simulators to understand driver behavior on interchanges (*12, 13*), and others that developed speed prediction models on curve ramps mostly on the basis of speed data measured by loop detectors (*14*). These studies are described in more detail in the section that follows.

CRASH PREDICTION MODELS

Bared et al. compared two types of interchanges (i.e., tight diamond and single point interchanges) with a negative binomial model to predict the total number of accidents and the number of accidents that caused injury and fatality (*6*). They found that single point urban interchanges were safer with respect to injury and fatality frequencies. Iliadi et al. also used negative binomial regression to develop a crash prediction model for weaving sections and found that weaving sections inside interchanges had a higher crash frequency than sections outside interchanges (*8*).

Parajuli et al. developed safety performance functions for interchanges, ramps, and ramp terminals for Ontario, Canada, freeways with negative binomial regression modeling, which related crash

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frequency to traffic volume and basic entity characteristics (*9*). Garnowski and Manner also developed a negative binomial regression model with random coefficients to understand which factors explained accidents on German Autobahn connectors (*15*). The data set included 197 ramps [69 egress ramps (in diamond), 33 loop-ramps (in cloverleaf), 95 tangent ramps (right connectors in cloverleaf)), and 3 years (2003 through 2005) of crash counts (total of 3,048 accidents). Traffic data were obtained from inductive loop detectors. It was found that the most important variable was average daily traffic. The fraction of trucks and measures of the curvature also were found to be important. The length of the deceleration lane, the width of the lanes, and the position of the steepest curve had effects only when they exceeded certain thresholds.

Broeren et al. analyzed the relationship between the design aspects of ramp curves at interchanges and crash rates in the Netherlands (*11*). On the basis of the results, they conducted an in-depth analysis of the speeds on ramp curves with high crash rates. They found that curves with high crash rates had small angular displacements, radii in the range of 200 to 400 m, were part of compound curves, and had low traffic volumes.

The main disadvantage of statistical crash prediction models is that they do not provide insights into driver behavior but only some correlational relationships between crash frequency and traffic and geometric characteristics. Further, the use of such models is a reactive approach, which depends on the quality and reliability of the crash records and registration (*16*).

Driver Behavior and Driving Simulators

Driving simulators, whose use is the other mainstream method of research on this topic, can provide insights into driving behavior. Bella summarized the studies in the literature that used driving simulators in geometric design studies in relation to driver behavior. His study provided an overview of the primary experiences acquired through the use of advanced driving simulators and pointed out their potential as well as their limitations (*17*).

FHWA used the Highway Driving Simulator to evaluate the design of a diverging diamond interchange before it actually was constructed (*13*). The purpose of this experiment was to observe drivers as they negotiated diverging diamond interchanges without an introduction to the design. Seventy-four licensed drivers from the Washington, D.C., metropolitan area participated in this experiment. The driving simulator experiment revealed sight distance problems, which led to unintended driver behavior.

Few driving simulator studies have focused on interchanges. Besides, driving simulator studies have several disadvantages: drivers experience no real sense of risk, and the results depend on the fidelity and validity of the simulator.

Speed Data from Field Studies

Liapis et al., conducted observational studies to measure speeds at 20 curve ramps of minor interchanges (known as service interchanges) in Greece with magnetic counters (*14*). Speed data on passing vehicles were collected at the middle of each circular curve and at the start and end points of the entry and exit clothoids. There, data were used to develop a model to predict the operating speed as a function of the curvature change rate, available sight distance, grade, superelevation rate, pavement width, and paved shoulder width. The authors found that the operating speed was influenced mostly by the curvature change rate and the superelevation rate. Montella et al. indicated that such studies, which had their bases in spot speed data and similar methods, made some invalid assumptions about driver behavior modeling (i.e., constant operating speed throughout horizontal curves; acceleration and deceleration only on tangents) (*18*). Thus in their study they used an instrumented vehicle with GPS continuous speed tracking to analyze driver speed and acceleration behavior on rural motorways in Italy to develop operating speed prediction models. They found that driver speeds were not constant along curves, the maximum speed reduction of an individual driver was greater than the operating speed difference in the tangent-to-curve transition, and the deceleration and acceleration rates experienced by individual drivers were greater than the deceleration and acceleration rates used to draw operating speed profiles. However, the instrumented vehicle study covered only a limited sample of drivers, who knew that they were being observed, which might have resulted in inauthentic driving behavior.

Research Gaps and Conceptual Model

As can be seen from the review of the literature, almost no studies have been conducted to analyze driving speed behavior on horizontal ramp curves in interchanges with field trajectory data. Thus the main goals of this present study were (*a*) to gain insights into the driving speed behavior of road users upstream and along the curves of different types of connections at interchanges in the Netherlands and (*b*) to understand the implications for road design and safety. To achieve these goals, the following conceptual model was used.

As shown in Figure 1, the frequency and severity of accidents stem from several contributing factors (e.g., road design, human factors, environment, and vehicle characteristics). This study investigated the impact of road design characteristics on longitudinal driving behavior (i.e., speed and acceleration) and the consequences of behavior (e.g., speed profiles, speed variability, and operating speeds).

The following research questions, related to longitudinal driving behavior, were investigated:

1. What are the speed profiles of drivers on different types of connections and as a function of the curves radii?
2. How do the observed driving speeds compare with the design speeds?
3. How much time does it take drivers to make the speed adjustment (deceleration) relative to the nose?
4. Which factors play significant roles in the prediction of the operating speed?

Lateral behavior was not addressed, despite its importance to an understanding of driving behavior. The comprehensive analysis that is entailed of the lateral movements of vehicles will be part of a follow-up study.

RESEARCH METHODOLOGY

The following paragraphs describe the research methodology adopted in this study, including the research approach, location selection, data collection, and the analysis technique.

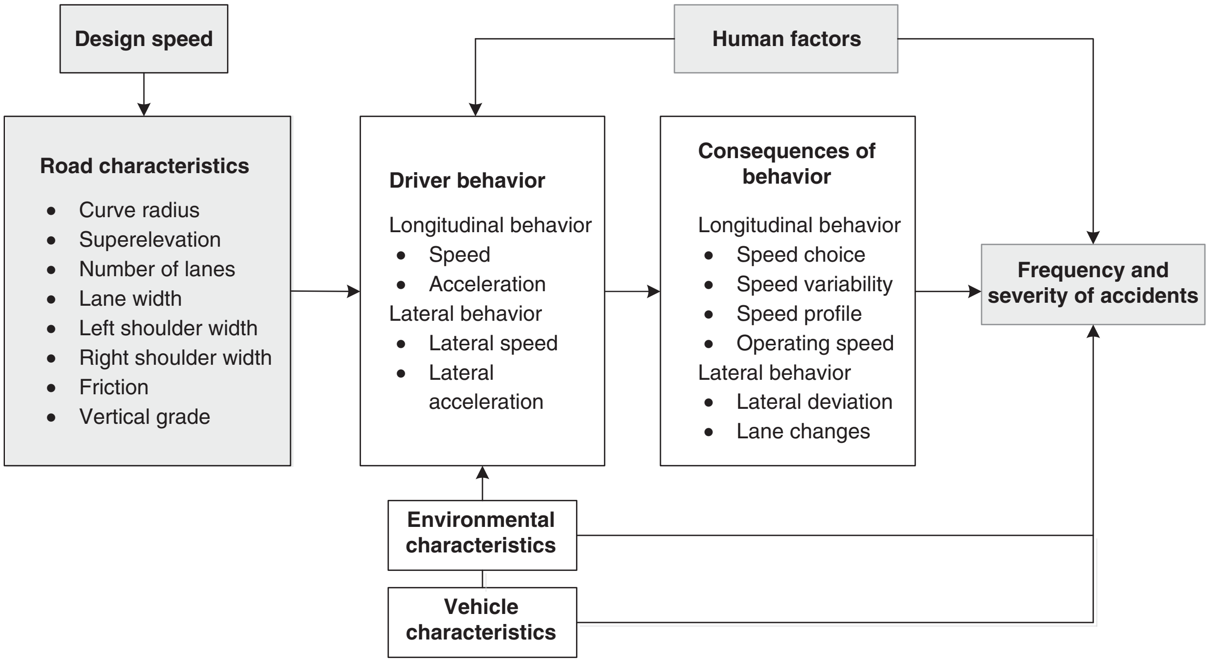


FIGURE 1 Conceptual model for driving behavior on curves.

Research Approach

In accordance with the defined objective of this study, detailed trajectory data of free-moving vehicles on various interchanges were needed to analyze vehicle speed behavior. Only free-moving vehicles were chosen, because the main objective was to understand how the road geometric design affected driving speed (i.e., excluding the impact of leading vehicles). In this study, a free-moving vehicle was defined as one whose predecessor was at least 100 m ahead of the tracked vehicle. Data were collected from video images taken from a high vantage point: a hovering helicopter.

Location Selection

The objective was to select different types of interchanges in the Netherlands, which lead to different types of connections and different road design characteristics. The following interchanges were selected: one half-turbine, three turbine-cloverleafs, one left trumpet, and one right trumpet. These six interchanges included 29 curves with different radii, superelevation, and number of lanes. In total, the horizontal curves were part of nine direct connections (mostly right-turning traffic), 12 semidirect connections (turbines), and eight indirect connections (loops), as illustrated in Figure 2. The numbers (in yellow) on the curves indicate the curve number, as shown in Table 1, which summarizes in more detail the characteristics of the selected curves.

The choice of specific interchanges, on the basis of the defined types, was restricted by the distance from the helicopter airport to the interchange. The flight time to the location and the minimum time period in which to collect sufficient data limited the number of interchanges within reach of the airport.

The design of horizontal curves in ramps at interchanges in the Netherlands has its basis in the design criteria of Dutch road design guidelines (*19*). The road geometry of ramps is determined by the design speed. The Dutch road design guidelines prescribe three standard design speeds for connectors: 50, 70, and 90 km/h (*11*).

On the curves selected for this study the truck percentage (on the basis of observed data) ranged from 0% to 28% (average = 11%, standard = 7%). The percentage of trucks could have had a significant impact on the operating speed, especially on ramps with only one driving lane.

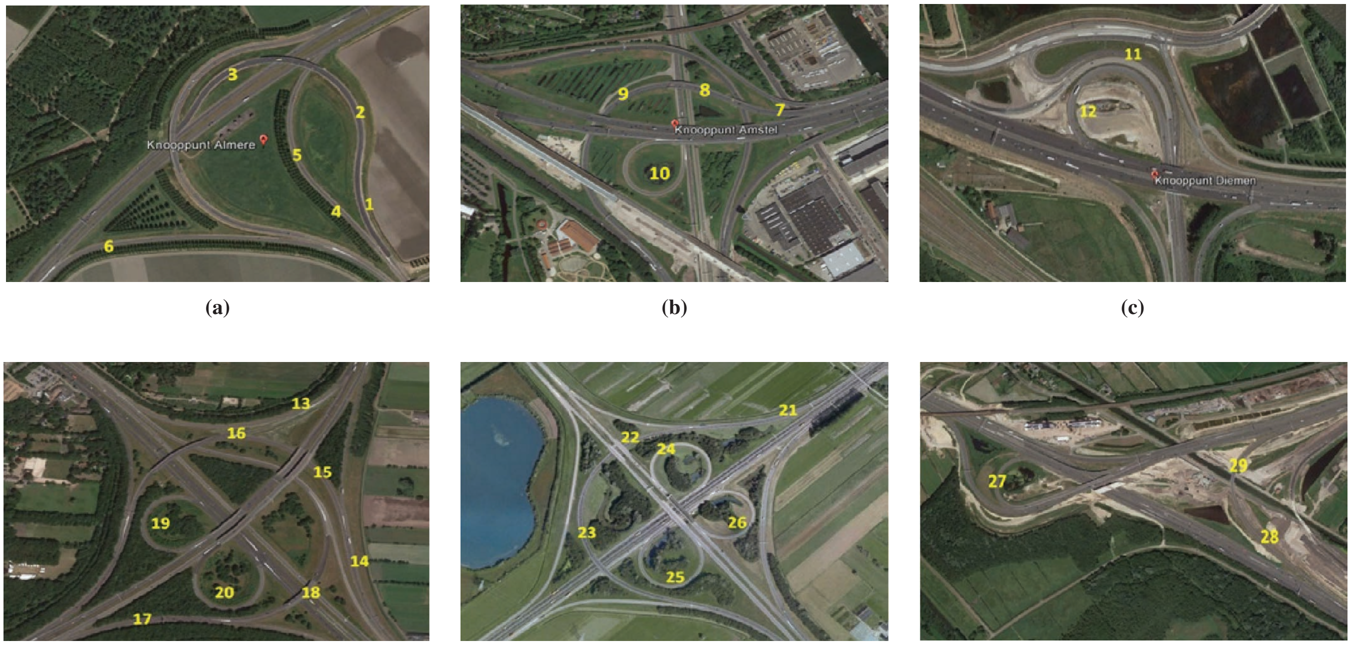
Data Collection

Trajectory data on free-moving vehicles were derived from stabilized video images taken with a frame rate of 12 images per second from a camera mounted underneath a hovering helicopter above each interchange for 25 to 30 min. A Prosilica Giga E5 megapixel camera with a Pentax lens was used. The trajectory data were collected during mostly clear weather; the wind direction was north, with a speed of 3 to 5 m/s. The helicopter hovered at a height between 450 and 550 m, depending on the size of the interchange. The obtained images were stabilized with a dedicated tool, called the ImageTracker, developed at the Delft University of Technology. For information on the applied method to stabilize the aerial traffic images and derive the trajectory data, see Knoppers et al. (*20*).

Besides the vehicle trajectories, information on the geometric design of the selected interchanges, and more specifically the curves' features (e.g., the number of lanes, radius, and superelevation) were obtained from Civil3D maps acquired from the Dutch National Road Authority (Rijkswaterstaat). The curve radii were measured from the white marking on the left side of the road.

Analysis Technique

To answer the research questions in this study, the trajectory data of the vehicles needed to be analyzed and processed to calculate



(a) (b) (c)

(d) (e) (f)

FIGURE 2 Selected curves for study: (*a*) Almere, (*b*) Amstel, (*c*) Diemen, (*d*) Eemnes, (*e*) Hattemerbroek, and (*f*) Muiderberg.

individual vehicle speeds. To derive the vehicles' speeds from the trajectories, a filtering technique was applied to reduce the noise in the data, which was caused by inaccuracies in the detection of the vehicles. For this purpose, the Fast Fourier transform algorithm was applied (*21*).

The data were analyzed in three steps: first, an analysis at the individual level (i.e., speed profiles of single vehicles were produced to understand drivers' speed behavior). Second, an analysis at the aggregate level was conducted by aggregating the speeds and correlating them with road design features (e.g., curve radius, and type of connection). Third, the operating speeds were calculated for each curve, and an operating speed prediction model was developed through linear regression analysis. Analysis of the semidirect connections was conducted in two steps. In the first step, the different curves that constituted each connection were analyzed separately to understand the impact of the curve radius on driving speeds. In the second step, the curves of each connection were analyzed together to understand the speed evolution along the connection. Further elaboration is provided in the sections that follow.

RESULTS

Analysis at the Individual Level: Speed Profiles

Speed profiles were created to illustrate the changes in the driving speeds of the observed vehicles as they approached and negotiated the different curves. Figure 3 presents several examples of these speed profiles, which are discussed in the following paragraphs.

Comparison of Indirect and Semidirect Connections

Figure 3*a* presents the speed profile of an indirect connection, while Figure 3*b* presents the speed profile of a semidirect connection of the Amstel interchange. The 0 m point in both figures refers to the beginning of the ramp nose. As can be seen, the drop in the individual speed of vehicles as they traveled on the indirect connection was higher than it was on the semidirect connection. On the semidirect connection, however, it can be seen that some vehicles actually increased their speed as they approached the curve, and there was more heterogeneity in drivers' speed behavior. This result can be related not only to the differences in the radii of the curves but also to the number of driving lanes. The indirect connection had only one lane, which meant that slow-moving trucks could not be overtaken, whereas the semidirect connection had two lanes. An increased number of lanes was found in the literature to increase driving speeds (*22*). Both connections had similar longitudinal slopes of about 3%.

Comparison of Right Trumpet and Left Trumpet

In the data set there were two trumpet interchanges. One was a left trumpet (Figure 3*c*) and one was a right trumpet (Figure 3*d*). Both had similar negative longitudinal slopes (1% to 3%) and a design speed of 50 km/h. As can be seen, the speeds in both connections were higher than the design speed, and the speed drop in the right trumpet (average = 30.19 km/h, standard = 7.50 km/h) was more evident and consistent than in the left trumpet (average = 20.50 km/h, standard = 8.60 km/h). An independent sample *t*-test revealed that the difference in the speed reduction in these two cases was statistically significant (*t*-test = −5.71; significance <.0001), which may have occurred for three possible reasons: (*a*) in the right trumpet, drivers on the main freeway faced the tight loop without necessarily having received signals to slow down sufficiently (whereas in the left trumpet, the loop was on a ramp); (*b*) the right trumpet connection had one driving lane, whereas the left trumpet connection had two; and (*c*) the radius of the right trumpet (77.9 m) was sharper than

TABLE 1 Characteristics of Connectors

Curve No.	Interchange Type	Connector Type	Design Speed (km/h)	Radius (m)	Turning Direction	No. of Lanes	Observed Vehicles (*n*)	Observed Trucks (*n*)
Almere (A27, A6)								
1	Half turbine	Semidirect	70	300	R	2	63	2
2		Semidirect	70	205.1	L	2	57	16
3		Semidirect	70	205	L	2	60	4
4		Direct	70	2,175	L	2	92	8
5		Direct	70	238.5	R	2	42	8
6		Direct	90	222.1	R	2	53	7
Amstel (A10, A2)								
7	Turbine–cloverleaf	Semidirect	70	225	R	2	47	9
8		Semidirect	70	230	R	2	108	13
9		Semidirect	50	174	L	2	50	2
10		Indirect	50	55.7	L	1	40	1
Diemen (A9, A1)								
11	Left trumpet	Semidirect	70	112.8	L	2	39	4
12		Indirect	50	81.2	L	2	60	4
Eemnes (A27, A1)								
13	Turbine–cloverleaf	Direct	90	447.3	R	1	52	8
14		Direct	90	460	R	2	63	12
15		Semidirect	70	280	L	2	61	4
16		Semidirect	70	250.7	L	2	75	6
17		Direct	90	670	R	2	56	2
18		Semidirect	70	216.6	L	1	56	5
19		Indirect	50	76.6	R	1	33	1
20		Indirect	50	76.9	R	1	68	9
Hattemerbroek (A28, A50)								
21	Turbine–cloverleaf	Direct	90	465	R	3	68	11
22		Semidirect	90	375	L	2	43	7
23		Semidirect	70	254.9	L	2	11	0
24		Indirect	50	77.6	R	1	7	1
25		Indirect	50	77.7	R	1	11	1
26		Indirect	50	67.8	R	1	40	9
Muiderberg (A6, A1)								
27	Right trumpet	Indirect	50	77.9	R	1	106	6
28		Direct	90	370	R	1	84	7
29		Direct	70	157.7	R	1	63	2

NOTE: R = right; L = left.

the left trumpet (81.2 m), although this difference was small and almost negligible. These results indicated that there might be a need to apply extra measures (e.g., more visible speed warning signs) to increase the awareness of drivers as they approach a right trumpet and that they should reduce their driving speeds gradually.

Comparison of Semidirect Connections

To analyze the semidirect connections, trajectory data observed on the curves that belonged to the same semidirect connection were combined to provide a full picture of how the driving speed profile evolved on these compound successive curves that constituted the connections. With the use of this method, the following curves were joined: 1–2–3; 7–8–9; 14–15–16; and 21–22–23 (curve numbers as indicated in Table 1). Figure 3, *e–h*, presents the speed profiles of these four semidirect connections. Because different vehicles were tracked on each of the curves that constituted a connection, discontinuities could be noticed along the connections. All of these connections had two lanes to allow faster vehicles to pass slower vehicles and heavy trucks. As can be seen in Figure 3, *e–h*, the variability in the speeds of drivers was much more than the variability in the speeds along the different curves. The analysis at the aggregate level elaborates further on this point.

Analysis at the Aggregate Level

First, a general analysis was conducted to understand how the driving speeds were related to the radii of the curves and the types of

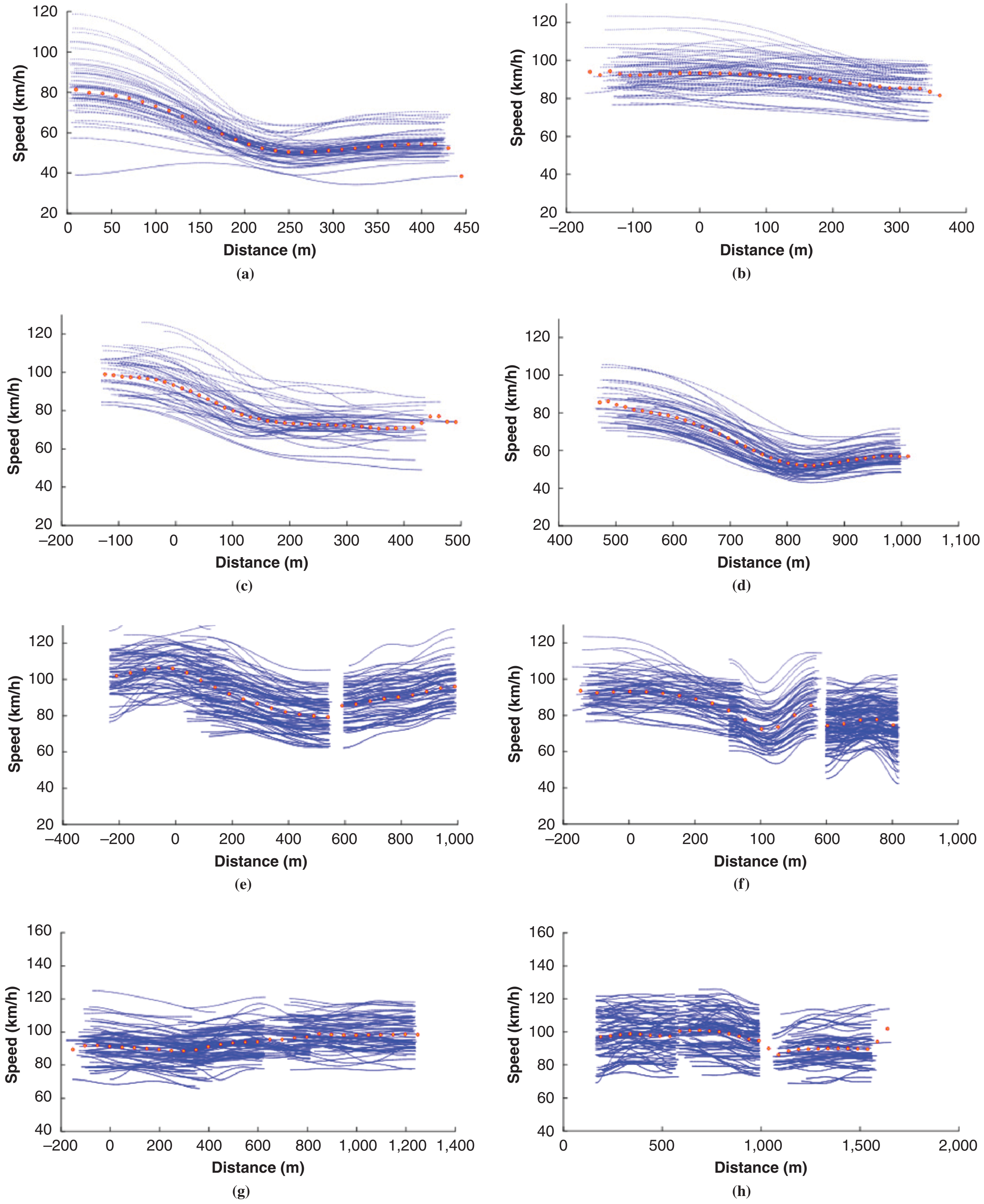


FIGURE 3 Vehicle speed profiles on curves: (*a*) Amstel indirect connection (Curve No. 10, 60-m radius; (*b*) Amstel semidirect connection (Curve No. 7, 225-m radius); (*c*) Diemen left trumpet (Curve No. 12, 81.2-m radius); (*d*) Muiderberg right trumpet (Curve No. 27, 77.9-m radius); (*e*) Almere semidirect connection (1–2–3); (*f*) Amstel semidirect connection (7–8–9); (*g*) Eemnes semidirect connection (14–15–16); and (*h*) Hattemerbroek semidirect connection (21–22–23). Red circles represent average speeds.

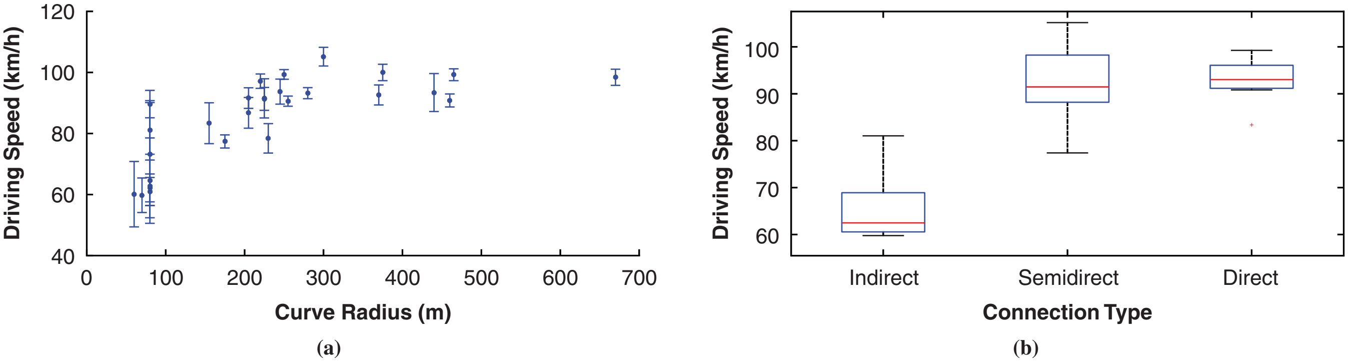


FIGURE 4 Average driving speed and standard deviation for (*a*) curve radii of connections and (*b*) median, 25%, and 75% percentiles for connection types.

connectors (i.e., direct, semidirect, and indirect). Figure 4*a* summarizes the results of the average and standard deviations of speeds of free-moving vehicles as they negotiated the different curves, while Figure 4*b* presents the median, 25%, and 75% percentiles as functions of the connection type.

As Figure 4*a* shows, the curve radius that increased driving speeds also increased, and this correlation was significant (correlation = .72; significance <.0001). As also can be seen, there was more speed variability in general on curves with radii of less than 100 m. This finding also is evident in Figure 4*b* for direct connections, which usually are characterized with larger radii. The driving speeds were higher than they were at the indirect connections, while the speed variability was lower than it was for the semidirect and indirect connections. The median driving speed at the indirect connections, however, was relatively lower, whereas the speed variability was higher. Broeren et al., who analyzed the relationship between crash rates and the radii of ramp curves in interchanges in the Netherlands, found that ramp curves with a small radius had higher crash rates than those with larger radii (*11*). This finding and the results on the indirect connections led to the same conclusion: small radii lead to high speed variability and, as a result, to accidents. Finally, for the semidirect connections, the median driving speeds and the speed variability were higher than they were for the indirect and direct connections. High driving speeds and large speed variability have negative effects on traffic safety (*3–5*). The following subsections analyze the speeds of the indirect and semidirect connections individually.

Cloverleaf Type (Indirect)

In the data set, there were six indirect connections, which were part of cloverleaf or partial cloverleaf interchanges. The speed characteristics of these curves are presented in Table 2. The results showed that the operating speeds (85th percentile of the observed speeds) were 15 to 28 km/h higher than the design speed, which could indicate a design problem.

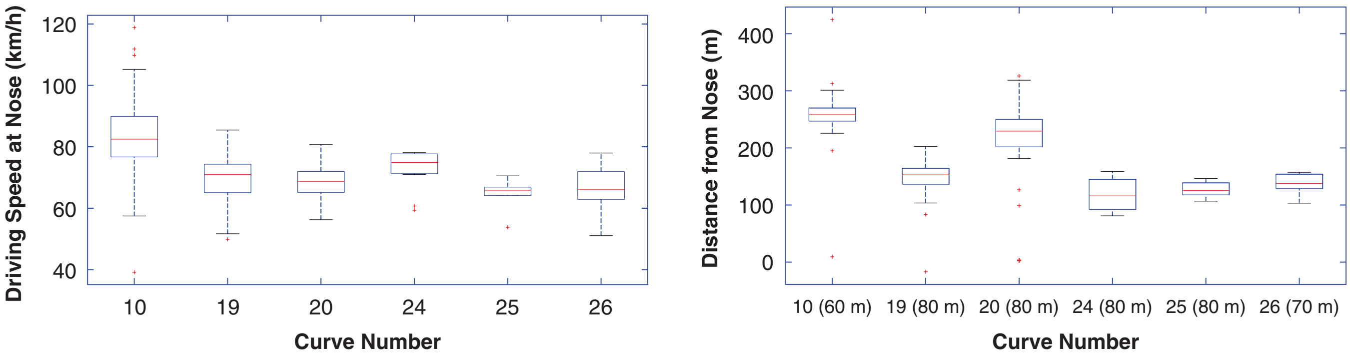
To further analyze the behavior of drivers as they approached and negotiated an indirect connection, their driving speeds were calculated at the nose (i.e., the location at which lane changes no longer are permitted), as well as the distance from the nose at which they reached the lowest speed (i.e., their deceleration distance from the nose). These results are presented in Figure 5.

The results in Figure 5*a* show that driver median speed and range of speed (25% and 75% percentiles) at the nose were highest for the curve 10 ($R = 55.7$ m). This Curve No. 10 had the smallest radius and was the only indirect connection in this interchange; all other connections were semidirect. Curves No. 19 and No. 20 constituted a half cloverleaf, and Curves No. 24, No. 25, and No. 26 constituted a partial cloverleaf (only one connection out of four was semidirect). In an evaluation once more of the design of Curve No. 10, it can be seen in Figure 2 that the curve was placed almost directly after the viaduct and was poorly visible. This curve was compared with the other indirect curves, and it was seen that the noses at the other curves were much farther away from the viaduct. In other words, drivers entered this curve at high speeds, and the variability in

TABLE 2 Characteristics of Indirect Connectors That Are Part of Cloverleaf Interchange

			Speed (km/h)				
Curve No.	No. of Observations	Radius (m)	Design	Average	Standard	Operating	Slope (%)
10	52	55.7	50	60.12	10.71	66.16	3.3
19	61	76.6	50	60.99	4.58	66.30	–2.3
20	34	76.9	50	62.17	4.57	66.45	2.5
24	11	77.6	50	73.26	16.87	78.23	NA
25	8	77.7	50	64.56	13.99	68.15	–2.0
26	12	67.8	50	59.77	5.66	65.44	3.0

NOTE: NA = not available.



(a) (b)

FIGURE 5 Driving speed at (*a*) nose and (*b*) location relative to nose (0 m) when drivers reach minimal speed.

speeds indicated a lack of consistency in driver behavior, which might have indicated poor driver expectancy and predictability as a result of poor design.

Figure 5*b* presents the distance from the nose when drivers reached the minimum speed. For Curve No. 10, it can be seen that it took drivers a longer distance (~250 m) on average to decelerate. The reasons were because drivers started at higher speeds, as can be seen in Figure 5*a,* and the poor visibility of the nose. For the other curves (except for Curve No. 20), drivers reached the minimum speed in a distance between 100 and 150 m. When the average deceleration was examined that drivers applied to reduce their speeds as they approached the curve, it was found that the average deceleration at Curve No. 20 was the lowest (1.05 m/s^2), whereas in the other curves the average deceleration ranged between 1.45 and 2.97 m/s^2. Further investigation is needed to better understand the source of this difference in deceleration.

Turbine Type (Semidirect)

Speed variability along the turbine connections and the speed variability of drivers had negative consequences on turbulence and safety. The average speed variability along each connection was calculated as the average of the variability in the speed profile of drivers. To calculate the average speed variability of drivers, the semidirect connection was divided into subsections of 50 m. The variability in drivers' speeds was calculated for each of these subsections, and then the average of all subsections was calculated. Because the same vehicles were not traced along the three curves that belonged to the same subsection, these calculations were done separately for each curve that constituted a connection. Table 3 presents a summary of both speed variabilities for each of these connections.

As can be seen from Table 3, the variability in speeds of drivers was much larger than the variability in speeds along the different curves. As also can be seen, on some connections the operating speeds were much higher than the design speed (e.g., Curve No. 1 in Almere, Δ = 46.27 km/h), while on other connections (e.g., Curve No. 14) the difference was much less (Δ = 8.99 km/h).

Development of Operating Speed Prediction Model

To further understand the impact of the different road design characteristics on the average operating speed, a multiple regression type model was estimated. A backward stepwise elimination procedure

TABLE 3 Speed Variability Along Connections and Speed Variability Among Drivers

		Speed (km/h)			Average Standard of Speed Variability (km/h)	
Semidirect Connection	Curve	Design	Operating	Direction of Curve	Along Curves of Connection	Among Drivers
Almere	1	70	116.27	R	3.05	10.87
	2	70	98.14	L	5.03	11.09
	3	70	100.80	L	3.38	8.65
Amstel	7	70	100.88	R	3.74	8.96
	8	70	88.56	R	4.82	10.35
	9	50	88.11	L	2.15	10.39
Eemnes	14	90	98.99	R	2.13	8.96
	15	70	101.52	L	1.81	7.37
	16	70	109.38	L	1.58	8.95
Hattemerbroek	21	90	112.47	R	1.940	11.927
	22	90	112.28	L	2.688	10.907
	23	70	104.56	L	1.663	9.240

(i.e., the criterion was the probability of F to remove $\geq .100$) was adopted to identify significant variables that contributed to the prediction of the operating speed. Development of a separate model for each ramp type was not possible in this case because of the limited number of curves in each category. A relatively high correlation was found between the ramp type and the curves' radii (correlation = .776; p-value <.0001). The curves' radii variable was more informative and therefore was preferred to the ramp type when the model was developed. In accordance with this procedure, all candidate variables were included in the model at the beginning. Then an iterative testing procedure resumed with the deletion of variables and tests to see whether each deletion improved the model. This process was repeated until no further improvement was possible. Thus different combinations of variables were tested to determine the best model. The formulation is shown in Equation 1.

$$\mathrm{OS} = \alpha + \beta X_n + \varepsilon_n \tag{1}$$

where

OS = operating speed (dependent variable),
α = constant,
X_n = vector of explanatory variables (independent variables),
β = vector of corresponding parameters to be estimated, and
ε_n = error term.

Table 4 presents the estimation results of the multiple regression models. The results indicated that a number of geometrical design characteristics significantly affected the operating speeds of drivers. In Model 1 it was found that an increase in the number of lanes encouraged drivers to drive faster, while an increase in the road curvature and the percentage of heavy vehicles led to a decrease in the operating driving speed. These results were in accordance with the insights obtained from the analysis at the individual level (i.e., speed profiles). Wider lanes were found to have a negative impact on the operating driving speed. These variables together explained 89% of the variability in the operating speeds. The unexpected impact of the lane width could be related to the number of lanes (i.e., interaction effect). Thus a new variable was defined, which was the total width of the road (which took into account the number of lanes as well as the widths of these lanes). The results of this model estimation are presented in Table 4 (Model 2) and show that, when the new variable (i.e., total width of the road) was taken into account, its impact on the operating speed was positive. In the next iteration, an interaction term was added between the number of lanes (dummy variable: 0 if 1 lane, and 1 if 2 lanes) and the curvature. However, this interaction term was not significant. Finally, a third model was estimated, which included only the number of lanes, curvature, and percentage of trucks, because these variables were relatively easy to measure, and their estimated coefficients remained stable along the different iterations. This model turned out to explain 87% of the variability in the operating speed.

In all three models, the width of the right and left shoulder, the longitudinal slope, the superelevation, and the direction of the curve (left or right), did not have significant impacts on the operating speeds. Some of these variables were expected to have a significant impact on the operational speeds (e.g., longitudinal slope, and superelevation). Thus further investigation is required. Because in this study the total number of curves in the sample was relatively small, the number of explanatory variables that turned out to be significant in the models was limited.

Still, these developed models provide designers with a tool to estimate the operating speed during the design process and compare it with the design speed with a relatively few number of variables, and with an explanation for the large percentage of the operating speed variability.

SUMMARY AND CONCLUSIONS

The main objective of this study was to conduct an in-depth analysis of driver speed behavior on curves of different connection types (e.g., indirect, semidirect, and direct) at interchanges. For this purpose, detailed trajectory data on free-moving vehicles at 29 curves on six interchanges were derived from stabilized video images taken from a camera mounted underneath a hovering helicopter. Vehicle speeds were then calculated from the extracted trajectories.

The analysis of speed in relation to the geometric design of the different curves showed that, when the radius of the curve was larger, the average driving speed was higher. Thus the average driving speed on semidirect and direct connections (which normally have larger curve radii) was higher than those on indirect connections. However, on indirect connections, the variability in speeds was higher. On semidirect connections, the average speed and the variability in speeds were higher. Higher variability in speeds increased the prob-

TABLE 4 Backward Multiple Regression Analysis Results

	Model 1		Model 2		Model 3	
Variable	Estimated (SE)	*t*-Stat.	Estimated (SE)	*t*-Stat.	Estimated (SE)	*t*-Stat.
Constant	126.720 (11.622)	10.903**	106.956 (6.489)	16.482**	102.210 (6.108)	16.735**
No. of lanes	8.642 (2.724)	3.173**			9.468 (2.962)	3.196
Curvature (1/km)	−2.194 (0.326)	−6.739**	−2.874 (0.306)	−9.397**	−2.646 (0.298)	−8.878**
Lane width (m)	−6.870 (2.839)	−2.420*				
Percentage of trucks	−58.650 (16.916)	−3.467*	−49.172 (20.225)	−2.431*	−52.922 (17.750)	−2.981**
Road width (m)			1.892 (0.880)	2.151*		
Adjusted R^2	.890		.838		.870	
F-value	49.663		42.456		58.798	
F-value (significance)	<.001		<.001		<.001	

NOTE: SE = standard error.
*p-Value ≤ .05; **p-Value ≤ .001.

ability of accidents, and higher speeds had negative consequences on the severity of accidents. It was found that the speed drop in the right trumpet was more evident than it was in the left trumpet, which was explained by the differences in the number of lanes and by the expectancy effect, which was related to the location of the loop (on a ramp or end of a freeway). An analysis of indirect and semidirect connections revealed that the operating speeds were higher than the design speeds. AASHTO states that "The selected design speed should be a logical one with respect to the anticipated operating speed, topography, the adjacent land use, and the functional classification of the highway" (*1*). These results indicated a problem in road design. For the indirect connections, it was found that the location of the nose relative to the viaduct affected driver expectancy, as did the distance it took drivers to adjust their driving speeds. On the semidirect connections, it was found that the average speed variability of drivers was higher than the average speed variability along the connections. The harmonization of driving speeds by means of intelligent systems could benefit safety.

Finally, the operating speed prediction model revealed that the number of lanes, curvature, and percentage of trucks significantly affected the operating speeds. These models will provide designers with a tool to estimate the operating speed during the design process in the future. In addition, the results of this study provide useful knowledge to update the design requirements of horizontal ramp curves in interchanges so as to harmonize the design speeds with the speeds observed in the field.

Further research can expand this analysis by increasing the sample size of the interchanges and the number of observed vehicles, as well as by increasing the data set of the observed speeds (e.g., during different weather conditions). Other important infrastructure-related features should be included (e.g., the friction and condition of the pavement), as well as an investigation of the impact of the longitudinal slopes, superelevation, and the shoulder width. This study demonstrated that these types of data have potential to reveal insights into driver behavior during the negotiation of curves. Future work will attempt to develop operating speed models that use the speed trajectory data without aggregation, to fully use the potential of these data to understand driver behavior, as well as to analyze driver lateral behavior on curves. Finally, the relationship between observed speeds and their variability with relevant surrogate safety measures would be useful to understand the implications of road design on safety.

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