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Speed Behaviour and Traffic Safety in Connector Roads Second Curves

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ABSTRACT

In the Dutch freeway geometric design guidelines, there is a rule that in connector roads, the second curve should not be smaller than the first curve in a connector road, so there is no need to decelerate further inside the connector road. By this it is assumed to match the expectation of the driver. Based on speed profiles in free flow situations and accident data, this research compares speed behaviour and accident risk in second curves which do or do not adhere to this rule and compare those to single curves as a baseline. In general, it can be concluded that the first curve does set expectations for the second curve which is seen in speed behaviour the curve approach phase of the second curve. Furthermore, the ratio of first and second radius is of influence to the speed at curve start of the second curve. The speed inside the curves is not different by using different radii for the first curve and comparable to single curves. The different speed behaviour in second curves for adhering to the design rules or not is however relatively small and does not seem to have an influence on accident risks.

Keywords: Consecutive curves, Speed behaviour, Accident risk

INTRODUCTION

One of the rules introduced in the geometric design guidelines for freeways in the Netherlands, is that in connector roads in interchanges, the first curve should have the smallest radius (*ROA*, 2015). By setting this rule it is assumed to match the expectation of the driver, who does not expect to decelerate further along the connector road. This means the second curve in a connector road should have a similar or larger radius than the first curve, as shown in **Figure 1**.

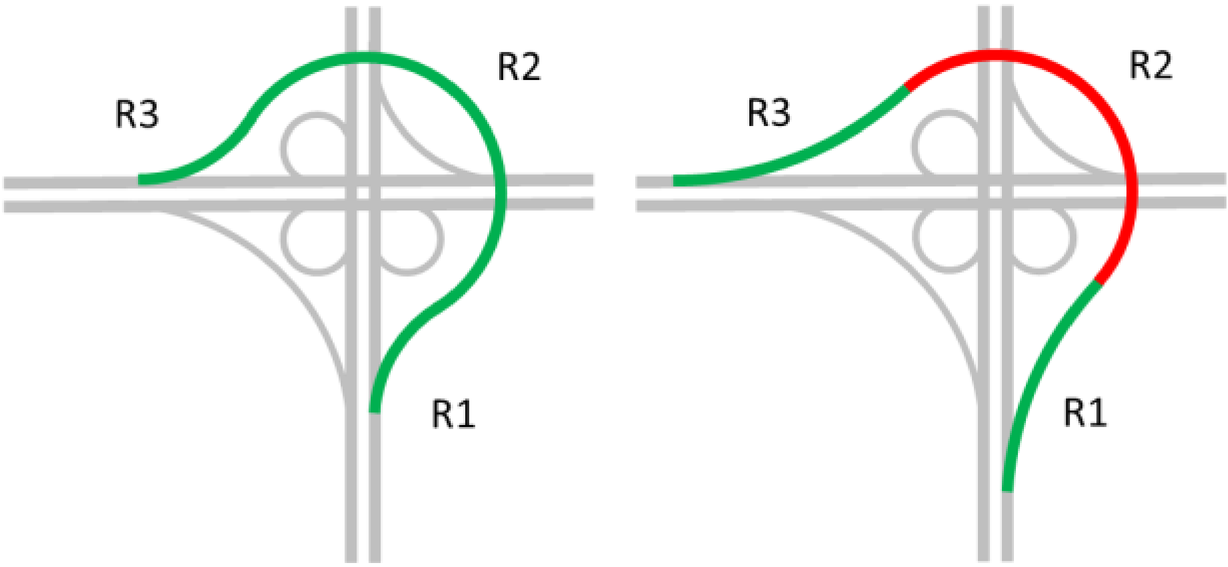

Figure 1 On the left a connector road which adheres to the rule of keeping the radii the same. On the right a connector road which has a smaller radius in the second curve than the first curve which might lead to wrong setting of expectations

This rule is stricter than normally set for design consistency (Lamm, Choueiri, Hayward, & Paluri, 1988), which uses speed differences between consecutive design elements to set consistency categories. Usually when the $\Delta V85$ between two consecutive design elements is lower than 10 km/h, it is classified as good, when the $\Delta V85$ is between 10 and 20 km/h it is classified as fair, and higher than 20 km/h is classified as poor (Kim & Choi, 2013; Luque & Castro, 2016).

The effect of this rule needs to be measured via the expectation setting of the drivers. That is hard to quantify, but drivers will decrease their speed based on a risk and comfort assessment of the upcoming curve (Campbell et al., 2012; Gibson & Crooks, 1938; Summala, 2007). So, analysing speed profiles can show insights in curve expectations, since speed profiles very clearly show the speed behaviour through the connector road (Dias, Oguchi, & Wimalasena, 2018). Furthermore, it is known that drivers tend to keep decelerating after the constant curve has started (Montella, Galante, Mauriello, & Aria, 2015; Vos, Farah, & Hagenzieker, 2021). So, gaining insights in speed development in the approach phase curves assumes to gain insights in driver expectation in curve approach.

Secondly, insights in the objective traffic safety effects of this rule will give further insights in the effects of the rule.

This paper will set a baseline for curves which are not influences by other curves (single curves) for speed behaviour and traffic safety, and test the differences in second curves which do and do not adhere to the design rules.

The following section will briefly discuss the methods used to check these differences. The third section analyses the speed and traffic safety data. The final section discusses the analysis and draws conclusions from the analysis.

METHODS

The analysis of this study uses the dataset obtained by Vos et al. (2021), which contains detailed geometrical information of 153 curves in The Netherlands and 996,375 individual free-flow speed profiles in those curves. The speed profiles were obtained using High Frequency Floating Car Data (HF FCD) by setting the data collection frequency of the route navigation app "Flitsmeister" to 1 Hz along the selected freeway sections by the developer. This smartphone app is used by approximately 1.6 million users in The Netherlands – roughly 15% of all driver-licence holders. This database was enriched with traffic accident data per curve (VIA) in the years 2018 - 2020 and the average traffic day volume per connector road (Rijkswaterstaat) in 2019. From this database we selected the single curves to be used as a baseline. Single curve have tangent sections upstream and downstream of them, so the speed behaviour and traffic safety is not influenced by other curves. We also selected second curves from the database, and divided them in two groups. One group has a radius smaller than the first curve in the connector road, and is therefore not adhering to the design rule. The other group has a radius which is larger or equal than the first curve, and is therefore adhering to the design rule. In **Table 1** the summary of these groups is given.

TABLE 1 Summary of the Curve Groups

	Single curves	Second curves	Second curves smaller than first curve	Second curves larger or equal than first curve
Number of curves	47	41	28	13
Average radius (m.)	301	257	210	359
Average length (m.)	432	344	355	323
Average deflection angle (grad.)	112	105	120	73
Mode of number of lanes (range)	1 (1 – 3)	1 (1 – 3)	2 (1 – 3)	1 (1 – 2)

Speed profiles

Based on the individual speed profiles the 85th percentile of the hardest decelerations were calculated for each curve, as well as the 85th percentile of the speed at curve start and the constant speed in the curve. The constant speed in the curve is based on the position downstream of curve start, where drivers reset their deceleration to 0 m/s^2 again. Speed upstream of curve start are not analysed, because they are mostly influenced by the first curve of the connector road. It is assumed that the hardest deceleration, speed at curve start and speed in the curve are mainly influenced by the second curve itself. These variables are shown in **Figure 2**.

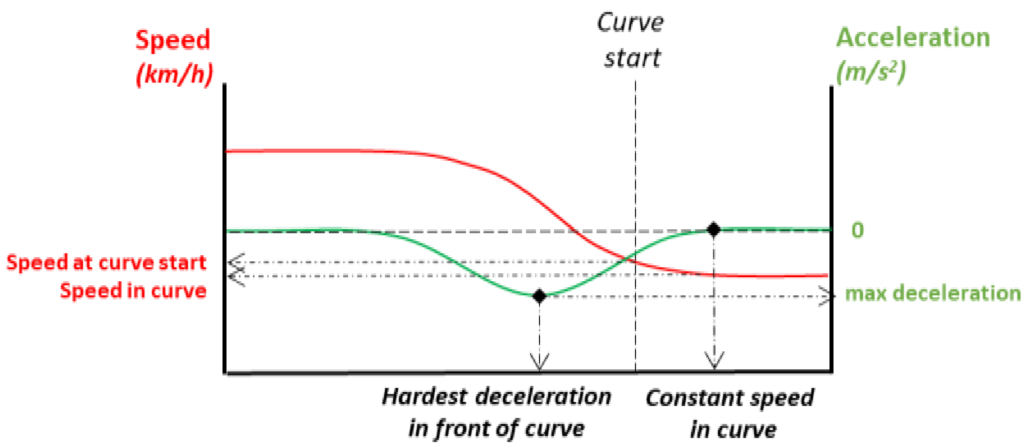

Figure 2 Theoretical speed and acceleration profile for curve approach, showing the variables which are analysed in this paper

The 85th percentile values are statistically compared per curve group in the data analysis section of this paper.

Accident risk

Using the accidents in the curves and the traffic volume data, we are able to generate an accident risk per curve applying **Equation 1** to the available data.

$$accident\ risk = \frac{total\ number\ of\ accidents\ in\ 2018-2020}{average\ day\ volume\ in\ 2019 \times length\ of\ curve} \times 1{,}000{,}000 \qquad (1)$$

The accident risks per curve are statistically compared per curve group in the data analysis section of this paper.

DATA ANALYSIS

The speed behaviour and accident risks are compared in the next two sections. As mentioned, the single curves are used as a baseline and are therefore shown in grey information in the figures in this section. The second curves are split up into two categories: with radii greater or equal to the first curve, hence adhering the design rule and shown in green, and a category with smaller radii then the first curve, and therefore not adhering to the design rule and shown in red.

Speed behaviour

The 85th percentile measurements are analysed in relation to the horizontal radius of a curve. In the scatterplots and regression lines in **Figure 3**, the three curve groups are compared.

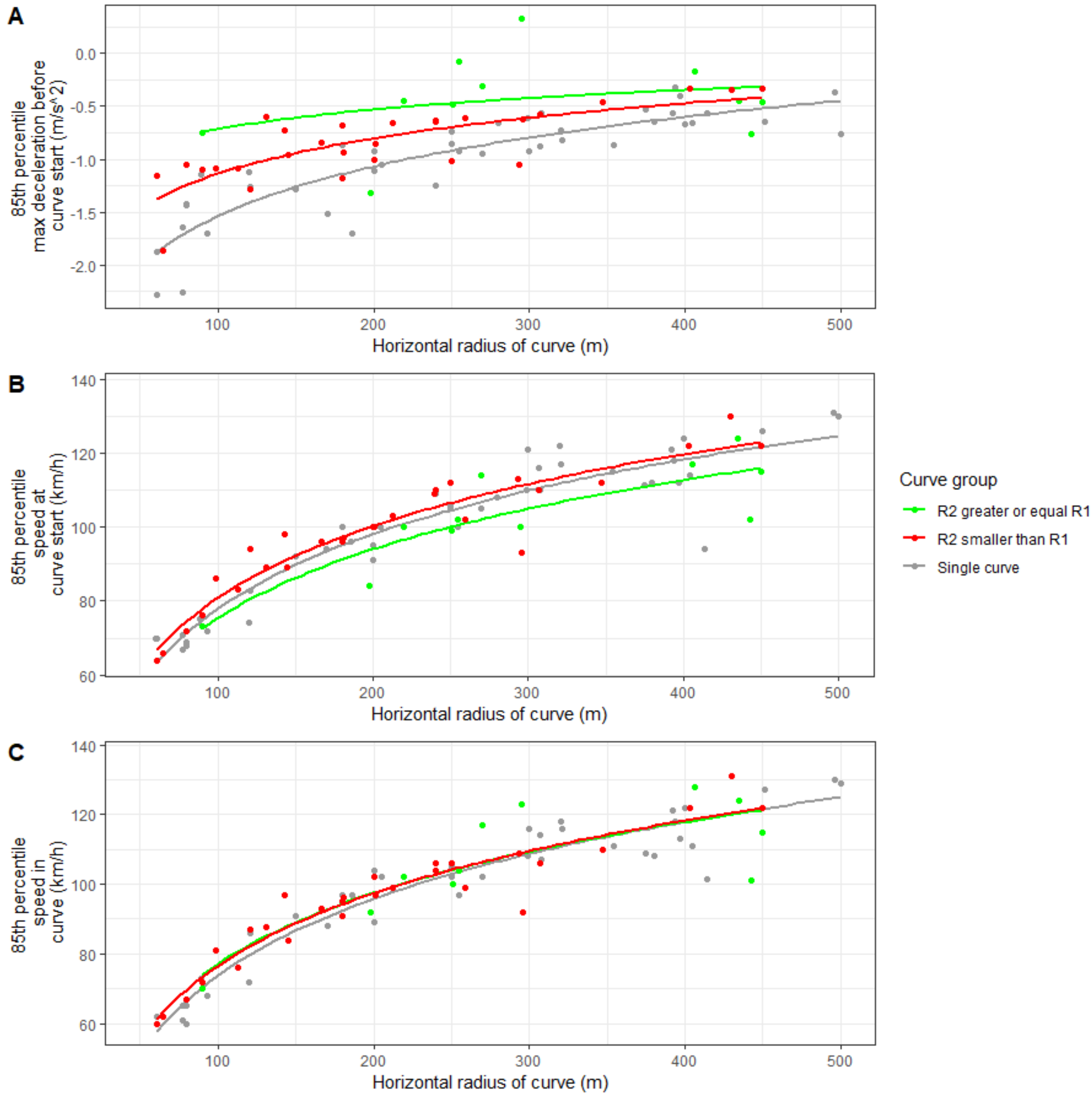

Figure 3 Scatterplots comparing speed behaviour for the three curve groups

In **Figure 3A** it is shown that drivers seem to decelerate less hard in front of a second curve compared to single curves. This is explained by the speed already being lowered by the first curve, in case the second curve larger or equal to the first curve. When the second curve is smaller, it might be because of wrong anticipation, but also because speed has already been lowered.

In **Figure 3B** it is shown that higher speeds are measured at curve start for second smaller curves compared to single curves. Especially in smaller radii, about 5 km/h higher speeds at curve start are noticed. Furthermore lower speeds are measured when the second curve is greater or equal than the first compared to single curves. Both are explained because at curve start drivers tend to still adjust their speed, so the first curve in a connector road influences the speed at curve start in the second curve.

In **Figure 3C** higher speeds are measured inside the second curve in general compared to single curves, but not as big a difference at curve start and neglectable onwards from radii higher than 300 m.

The regression lines in **Figure 3** are modelled in **Table 2**.

TABLE 2 Regression models for the regression lines shown in Figure 3

	85th percentile max deceleration (R2 >= R1)	85th percentile max deceleration (R2 < R1)	85th percentile max deceleration (single curves)	v85 at curve start (R2 >= R1)	v85 at curve start (R2 < R1)	v85 at curve start (single curves)	v85 in curve (R2 >= R1)	v85 in curve (R2 < R1)	v85 in curve (single curves)
Constant	-1.645	-3.336***	-4.496***	-32.708	-48.416***	-55.332***	-27.535	-61.870***	-70.041***
ln(Rh)	0.212	0.478***	0.646***	23.963***	28.070***	28.951***	23.679**	30.061***	31.279***
Num.Obs.	13	28	47	13	28	47	13	28	47
R2	0.088	0.613	0.802	0.765	0.902	0.920	0.638	0.909	0.942
R2 Adj.	0.005	0.598	0.798	0.744	0.898	0.919	0.605	0.906	0.941

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

The models predicting the relationship between horizontal radius and deceleration and speed for single curves all show a strong goodness of fit ($R^2 > 0.8$) and all variables show significance at levels at $p < 0.001$. This means that this baseline is good to be used to compare the other sets to.

The models predicting the relationship between horizontal radius and speed for second curves which are smaller than the first curve (and therefore don't adhere to the design rules) all show a strong goodness of fit ($R^2 > 0.8$). The model explaining the relation between radius and maximum deceleration shows a modest goodness of fit. All variables show significance at levels at $p < 0.001$. This means this set can be compared to the baseline.

The models predicting relationships for second curves which are equal or greater than the first curve (and therefore adhere to the design guidelines) have a relative low number of observations (n=13) and are therefore less reliable. The models predicting the relationship for speed and the horizontal radius all show a modest goodness of fit ($R^2 > 0.6$), but do not have a significant constant, so the height of the speed is not significantly predicted. The model explaining the relation between radius and maximum deceleration shows a low goodness of fit ($R^2 < 0.2$) including non-significant variables. This means the shape of the speed regression lines can be compared to the other speed models. The deceleration model cannot be compared to the other models because it has a very low explanatory value.

The models of the speed at curve start have the best explanatory value, and are of most interest, because they are related to expectancy setting by the upstream first curve. In **Figure 3B** it is shown that the curve group with a smaller radius in the second curve, has a higher speed at curve start than the baseline would suggest. In order to gain more insights in the relationship between the first and second curve, the ratio of sequential curve radii was analysed. The radius of the first curve is divided by the radius of the second curve to get the ratio R1/R2. So, a ratio equal or below 1 adheres to the design guidelines and a ratio above 1 does not. For each of the second curve radii, it was predicted what the 85th percentile speed would be if it were a single curve, based on the regression model of single curves, to set as a baseline. The difference between the predicted baseline speed and the actually measured 85th percentile speed at curve start is related to the curve radii ratio in **Figure 4**.

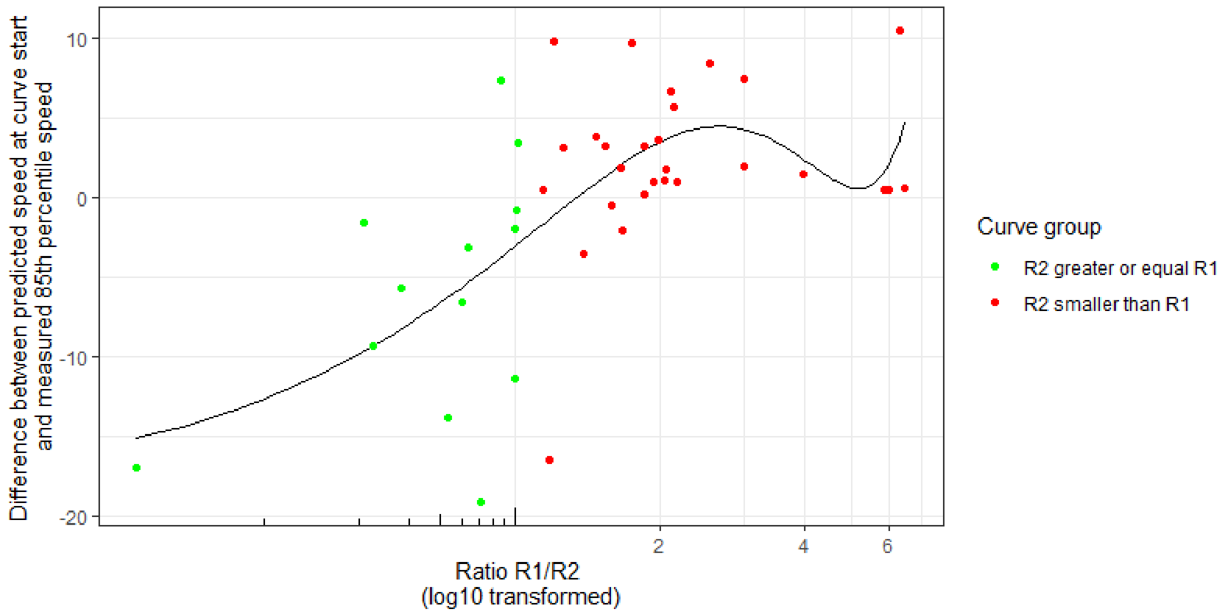

Figure 4 Scatter plot and fitted polynomial line of speed differences at curve start between *V85* in second curves to modelled single curve speeds, related to sequential curve radii ratio

Figure 4 shows lower speeds at curve start of the second compared to single curves with the same radius, if the first curve has a smaller radius. This is to be expected, because the speed in the first curve is dropped more than it would on the approaching tangent of a single curve. When the ratio R1/R2 is above 1.8, so when the second curve has a radius 1.8 times smaller than the first curve, all measured speeds at curve start of the second curve are above what would be expected, based on a curve approach with a tangent.

The fitted polynomial function with three degrees in **Figure 4** shows that generally, the speed at curve start will be above what is to be expected, around a curve radii ratio of 1.4. The polynomial function has however an R^2 of 0.43 ($p < 0.001$), so it has a weak goodness of fit.

Accident risk

To investigate the accident risk of the curve groups, the boxplots in **Figure 5** show the distribution of accident risks for the curves in the curve groups.

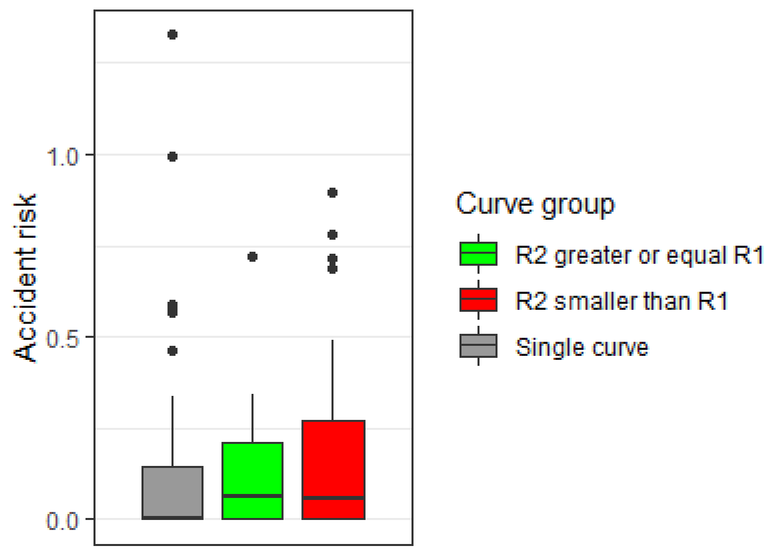

Figure 5 Boxplots of the accident risk per curve group

The boxplots in **Figure 5** show about the same distributions of accident risk across the curve groups. A Wilcoxon Signed-Ranks Test indicated that the accident risk in single curves (median = 0.00) is statistically not significantly different from the accident risk in second curves in general (median = 0.06), p = 0.41. Also, the accident risk in second curves which have larger or equally great first curves (median = 0.06) is statistically not significantly different from the accident risk in second curves which have smaller radii than the first curve (median = 0.06), p = 0.85.

To further investigate the accident risk in second curves, the accident risk is compared to the ratio of sequential curve radii to test the effect of design consistency (Lamm et al., 1988) on traffic safety and the measured speed differences at curve start in second curves to the baseline prediction to test the effect of presumed differences in expectations at curve start on traffic safety.

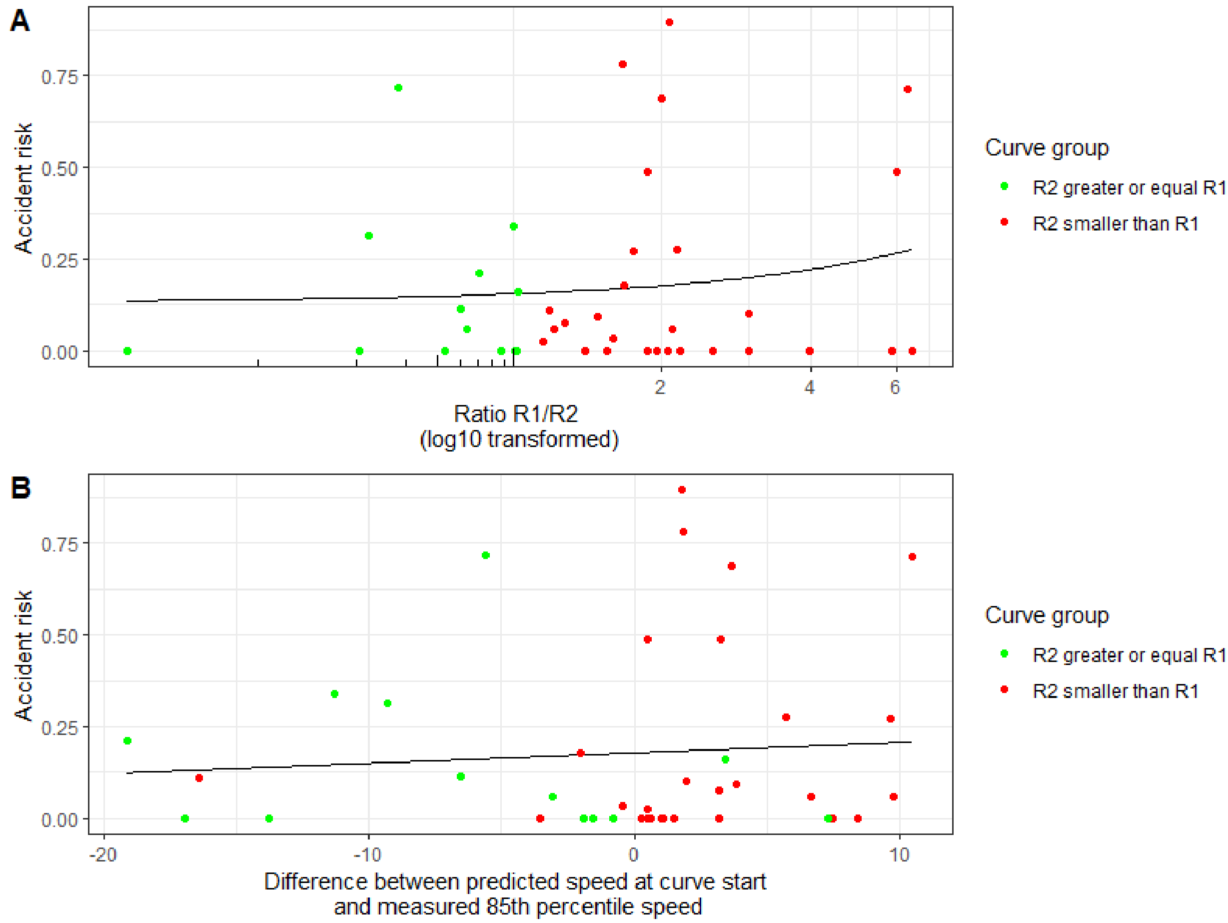

Figure 6 Accident risk in relation to sequential curve ratios and speed differences at curve start from baseline prediction to second curves

Figure 6A tends to show that with a larger ratio R1/R2 the accident risk increases, suggesting higher risk with more deviation from the design rules. However, the plotted regression line has a R^2 of 0.02 ($p = 0.4$), so no correlation between the two variables is shown.
Figure 6B tends to show that when the speed at curve start is higher than it would be when the curve is approached with an tangent, the accident risk increases. However, the plotted regression line has a R^2 of 0.01 ($p = 0.6$), so no correlation between the two variables is shown.

DISCUSSION AND CONCLUSION

This research was based on a dataset which was not intended for this research (Vos et al., 2021), so it lacked sufficient sample sizes in some curve groups. Especially the second curves which adhere to the design guidelines, were small in numbers (n=13), but also second curves which do not adhere to the guidelines had a low sample size (n=28). This results in difficulties finding strong and significant correlations. Some general conclusions can however be drawn from this research, although further research should obtain more curve samples, more in depth accident analysis about individual accident causes and gain insights in the effects of limiting sight distances.

Furthermore, the curve groups have different modes in the number of lanes. This is not analysed further, but this might also be an explanation for the differences in speed behaviour.

Drivers seem to drive a bit faster in second curves in general, compared to single curves. Especially for radii smaller than 300 m. At curve start of the second curve, the speed is influenced by the upstream first curve. When the first curve has a similar or smaller radius, the speed is lower at curve start than single curves, suggesting an approach of the second curve influenced by the lowered speed in the first curve. When the first curve has a greater radius, the speed at curve start is higher than in single curves, suggesting less well anticipation of the drivers on speed adjustment in the curve. Furthermore, the ratio of the first and second curve radius, has a relation to the speed at curve start of the second curve. The smaller the second curve is in relation to the first, the higher the speed at curve start of the second curve is. If the second curve has a smaller radius than about 1.5 times the radius of the first curve, the speed at curve start exceeds that of a regular curve, indicating wrong expectation setting by the first curve.

In accident risk however, no differences were found in any of the indicators for adhering to the design rules or not. This could be due to low sample sizes and under registration of accidents. But related to the relative small speed behavioural differences measured, no significant differences in accident risk are expected.

This study was done in The Netherlands, which is a relative flat country. So, no steep grades or hilly environments are tested. Dutch drivers are used to driving in these conditions, so both geometry and speed behaviour are specific for The Netherlands. These results therefore may not be transferred into other contexts.

In general, it is concluded that the first curve does set expectations for the second curve which is seen in speed differences at curve start of the second curve. The speed inside the second curves is not different by using different radii for the first curve. So, drivers still pick the same speed inside the curve as they normally would. Although the expectations for the second curve are influenced by the first curve, as shown based on speed profiles, no differences in accident risks are reported for different consecutive curves in connector road.

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