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A Case for Differentiating Design Consistency Evaluation Between Day and Night

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Abstract

A large percentage of fatal crashes occur at night: 47 percent in the USA and 36 percent in the EU and the nighttime traffic death rate is 4.4 times higher than in the day. Drivers rely on visual clues to complete the driving task and at night, they rely on their headlights to illuminate the distance ahead, which on average is about 160 feet. Thus, a possible contributing factor to higher crash rates at night is the reduced sight distance as it compares to that in the day. Studies have shown that speeds are virtually the same at day and night. These issues can become problematic at horizontal curves not providing drivers with adequate time to adjust their speed to safely negotiate the curve: a process that they can complete at daylight conditions. This study is the first step towards demonstrating the influence of horizontal curvature on nighttime crashes through a preliminary analysis. The objective of the study was to identify the magnitude of the problem and provide guidance for future research. Roadway segments from USA, Greece and Italy were examined and findings indicate that the increased crash occurrence at night could be related to the curve radius. Sharper curves showed an increase in crashes and crash rate when they were compared to their corresponding daytime crashes. Design consistency was evaluated using the radii of successive curves and the data supported the presence of differences in crashes between day and night. Additional work is needed to further explore these issues.

Keywords: Geometric design; Safety; Design consistency: Crash risk

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1. Introduction

Roadway designs are the result of an iterative process where design elements are balanced in order to develop an alignment that drivers can understand the roadway demands and use a safe speed to negotiate the various alignment components. In this manner, designers aim to provide the required clues to the driver through roadway features and traffic control devices and guide drivers in selecting comfortable speeds and adjust them as needed to address the various changes in vertical and horizontal curvature. Reliance on visual clues to complete the driving task is therefore essential and during the day it is easier to identify problematic conditions. At night though, drivers rely on their headlights to illuminate the distance ahead, which on average is about 160 feet (NHTSA n.d,). In addition to the shorter available sight distance, human vision is not very well adapted during the night and there are several other issues that can pose additional concerns to nighttime driving (Fors and Lundkvist 2009).

Crash statistics support the notion that night driving is more dangerous. Mace and Porter (2004) estimated that around 45 percent of traffic fatalities occur at night even though the number of vehicle miles driven at night represents about 14 percent of the total. They also showed that the nighttime traffic death rate of 4.63 deaths per 100 million vehicle miles, is 4.4 times higher than that in the day. Past research has shown that there is little, if any, difference in speeds between day and night on two-lane rural roads (Donnell et al. 2006; Mavridi et al. 2016). This fact underscores the need of investigation of the impact of geometry at nighttime, since it appears that drivers do not recognize the necessity to adjust their speeds to account for the reduced sight distance.

Horizontal curvature can magnify this issue due to reduced sight distance at night as it would compared during the day. Drivers may not be able to properly adjust their speed to accommodate the sharpness of the curve at night as they would have done in daylight conditions. It is therefore crucial to reconsider horizontal alignment under the scope of nighttime driving due to the limited stopping sight distance. Horizontal curvature changes that may require speed adjustment should be communicated to the driver and this becomes more critical at night due to the limited and shorter sight distance.

Driving at night is considered in general as less safe than daylight driving. Low luminance conditions such as those encountered during night driving can pose safety concerns, since the human eye is not very well adopted to such conditions. In addition, dark adaptation, which is a process of adjusting to the ambient light, and glare either from oncoming traffic or sign reflectivity are notable issues for night driving (Fors and Lundkvist 2009; Owens and Sivak 1993). Driving at night, drivers encountering bright light sources, such as headlights from an oncoming vehicle or reflections of headlights on signs, require time to adapt again to the dark conditions resulting in driving with limited vision. A study on the effects of glare and its potential impact on night safety concluded that glare is indeed an issue requiring attention and that there is the potential that glare can contribute to crash occurrence (Bullough et al. 2008).

Design consistency evaluates the transition of drivers between successive roadway segments aiming to identify potential problematic spots where drivers may fail to safely negotiate the upcoming segment. Current design consistency models have been developed based on data collected during daytime conditions. As noted above, prior research has identified the absence of significant differences in speed behaviour between day and night (Mace and Porter 2004; Guzman 1996; Mavridi et al. 2016). In addition, recent studies have examined the nighttime design consistency and they support the presence of differences in speeds of successive segments between day and night conditions especially with higher speed reductions on tangent to curve transitions at night identifying the need for additional design consistency evaluations for night conditions (Bela and Calvi 2013).

The literature reviewed here demonstrates that there is a need for additional evaluation of roadway designs for night conditions. There are no studies that have examined and documented the relationship between crashes and curvature under the scope of light conditions, which is a goal of this study. Most of the design consistency models consider only how a driver would transition from a tangent to a curve and there is little attention paid to consecutive curves and their safety implications and relationship with respect to their curvature. Moreover, all such models have been developed with daytime data and thus fail to consider the fact that nighttime lower visibility may compound the issues regarding the effect of successive curve radii. This study will address these issues and provide insights that can be used to improve design consistency while considering night conditions.

It is therefore critical to understand and examine the influence of roadway geometry, and especially curvature, and design consistency on nighttime crashes. This paper makes the case for the need for nighttime design consistency evaluation presenting the magnitude of the problem and providing guidance for future research.

2. Research approach

The analysis conducted here is based on roadway data and crashes along four two-lane rural road sections in Kentucky (USA), three in Greece and eight in Italy. For Kentucky, the roadway data was based on data collected from a Mandli vehicle as part of pavement scans on state-maintained roads. The roadway geometry was extracted from the scans utilizing the coordinates along the corridor. Pavement scans were also used for the Italian roadways and for one of the Greek roadways. The data collected consisted of the latitude, longitude and elevation of each point along the centerline of the travel lane. For the other two road sections in Greece, roadway geometry was obtained by an in-situ survey recording the centerline and pavement edges (sidelines) of the road. The FM17 road design software was utilized to transform these data into X, Y, and Z coordinates of the centerline and recreate the roadway alignment (Apostoleris et al. 2013). This process allowed for the identification of the curvature and superelevation of each curve along the alignment and the profile of each road. A separate evaluation of horizontal sight offset clearances for all curves was conducted and determined that none were present.

The Interactive Highway Design Safety Model (IHSDM) was employed to estimate the safety level of each segment (FHWA n.d.). The software is used for predicting the crashes along the corridor and identifies their potential locations. To address the lack of any safety performance functions (SPFs) or crash modification factors (CMFs) for nighttime crashes, two different models in the IHSDM were developed that predicted the day and nighttime crashes using the corresponding volumes. Historic crash data was utilized to adjust the crash prediction though the use of the Empirical Bayes Method. For all segments, only crash types that could be attributed to the curvature of the roadway were considered: ran off the road, head on and sideswipe opposite direction collisions. For each country, different crash periods were used (Kentucky 2006-2016, Italy 2011-2015 and Greece 2000-2015 for Domokos roadway and 2010-2015 for the other two roadways). The Property Damage Only (PDO) crashes were included since almost all are reported in Kentucky due to insurance claims. A final investigation was conducted to ensure that there were no interventions in the roadway alignment over the study period concluding that no changes were performed.

The historical traffic volumes for each segment were obtained and used for the development of crash rates and in the IHSDM prediction models. For the Greek roadways, actual traffic counts for day and night were available and utilized accordingly. On the average, the nighttime traffic was approximately 25 percent of the total. For the Italian roadways, recent historical actual traffic counts of the Average Annual Daily Traffic (AADT) were used and the average night traffic was considered to be approximately 25 percent of the AADT. For the Kentucky roadways, the night volumes were estimated based on a past research effort that developed guidance in estimating AADT based on short traffic counts (Allen et al. 1998) and the percent of night volumes was estimated to be 25 percent of the AADT.

For each roadway segment a separate crash prediction though the IHSDM was obtained to reflect the day and night crashes utilizing the corresponding volumes and crashes. The output of each IHSDM run was used to record the number of crashes for each curve. Design consistency is evaluated considering the impact of the preceding on the following curve and thus the radii of each pair of consecutive curves were evaluated. A weighted metric of the relevance between curves was established to distribute the crashes proportionally per direction considering the radii of the curves. Assuming that there are three consecutive curves with radii R1, R2 and R3 reached in ascending order, the crashes along curve 2 for the direction from curve 1 to 3 were considered to be prorated to (R1/(R1+R3)) while the opposite direction was prorated to (R3/(R1+R3)). This approach allows for evaluating design consistency considering the effect of a combination of curves and accounting for the potential influence of the proceeding curve.

3. Data

All roadway segments considered here are rural two-lane roads. The boundaries of built-up areas were determined through the use of aerial photographs in order to identify locations where street illumination may be present that could enhance sight distance, since the study objective is to examine the influence of curvature on nighttime crashes in areas without any illumination. In USA, the light conditions were based on the crash report ambient light information recorded: daylight was considered for crashes recorded as having occurred at day while nighttime included dawn, dusk and darkness. In Greece and Italy, the nighttime crashes were defined based on the time of each crash: day crashes were considered as those occurring between 7:00 and 20:00 for spring and summer and between 9:00 and 18:00 for autumn and winter. Each segment considered had such a built-up area and therefore each was broken into appropriate sections to eliminate these areas. Table 1 presents the sections and their characteristics. Crash rates are reported as crashes per million Vehicle-Miles of Travel (MVMT). The crash rates for the Domokos and all Italy sections are lower than the other sections because the only available crash data was for fatal and injury crashes.

Table 1. Trip attributes and safety evaluation of routes

Country	Segment	Length (mi)	AADT (vpd)	Crashes		Crashes/mil VMT		Number of Curves	Curve Radius (ft)		
				Day	Night	Day	Night		Min	Mean	Max
USA	KY 152	10.168	2,500	147	76	1.920	2.979	58	148	1,713	5,699
	KY 152	8.751	2,800	127	72	1.721	2.928	56	56	2,844	>6,000
	US 68	6.650	2,250	148	61	3.285	4.062	41	315	2,126	>6,000
	US 68	12.766	2,800	384	180	3.568	5.017	71	157	2,352	>6,000
Greece	Domokos	14.313	5,300	86	34	0.261	0.309	78	200	1,000	>6,000
	Tempi	6.000	3,000	31	16	1.054	1.633	47	330	1,650	>6,000
	Platamonas	6.469	3,000	76	30	2.397	2.840	33	200	1,350	>6,000
Italy	SP23	5.564	14,400	7	1	0.064	0.027	44	36	1,969	>6,000
	SP34	4.704	10,600	13	8	0.190	0.352	73	20	1,476	>6,000
	SP121	3.492	11,700	22	10	0.393	0.537	51	23	1,115	>6,000
	SS162	1.253	11,650	5	2	0.250	0.300	9	302	2,657	5,988
	SP498	1.927	19,800	11	2	0.211	0.115	13	240	2,461	>6,000
	SP510	1.420	16,600	6	1	0.186	0.093	9	374	5,249	>6,000

Nighttime crash rates are in general higher than those observed during the daytime. The minimum radii reflect the use of low design speeds while the mean radii values indicate an overall higher design speed. Most of the curves along the corridors have low advisory posted speed limits reflecting the potential danger for the curves if not accommodated properly. The data in Table 1 shows that for all 13 corridors there is a large overall frequency of curves with a rate of approximately 7-8 curves per mile. It should be noted here that the maximum curve radii noted are significantly greater than those recommended in the AASHTO Green Book. For this analysis, curves with radii greater than 6,000 feet were considered straight segments and the influence of the curve was deemed negligent. It should be noted that there is a difference on the traffic volumes among the three countries: Italian roads have significantly higher AADT. This could result in lower volumes at night in the USA and Greek roads resulting in more true free flow speeds. However, this was not considered a significant issue since the analysis considered crash rates as a safety metric.

All 13 segments have constant cross sections with 12-foot lanes. Shoulders were approximately 6 feet wide with adequate clear zones for the Kentucky roads and in level terrain (grades <3 percent). Greek and Italian roads had 5-foot shoulders with adequate clear zones and in mountainous terrain (absolute grades 1 to 7 percent).

4. Evaluation results

A hypothesis of this study is that there is a relationship between curvature and crash frequency and that this relationship is affected by the light conditions. Plots of the crash rates (crashes/MVMT) agree with the findings of prior research that correlate crash rates and curvature. Moreover, one can observe that nighttime crash rates are higher than those of daytime for the same curve radii. This verifies the hypothesis that higher crash emphasizing the notion that the curve radius has a greater impact on crash occurrence at night than during the day (Fig. 1). The limited roadway sample does not allow for any further statistical analysis or models that could correlate crashes to curve radii as they relate to light conditions. As noted, the IHSDM is employed to estimate the safety effects of the curve radius using two separate prediction models reflecting day and night conditions. These models estimated the number of crashes and crash rates and they were related along the corridors for each curve. The results show that in general the estimated number of crashes at night is greater than that during the day. The same observations noted with the crash rates in Fig. 1 hold in general true here as well: for the same curve radii, higher rates were observed at nighttime than during the day. This underscores the notion that the curve radius has a greater impact on crash occurrence at night than during the day. This difference is greater, and thus more critical, for sharper curves (i.e., with a small radius). Therefore, the suspicion that the sight distance at nighttime is significantly reduced and that the curve radius seems to be more critical at night than during the day is validated.

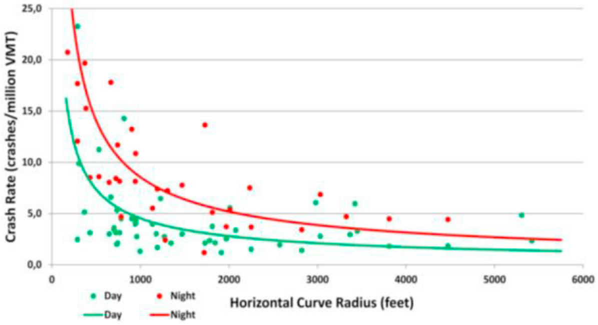

Fig. 1. Relationship between curve radius and crashes (a) Kentucky, USA

This study also aimed to examine the concept of design consistency as it would be manifested through the effect of the radii of successive curves on crashes. Design consistency here is based on the evaluation of the sequence of curves in order to identify acceptable radii combinations that would allow for appropriate transitions between curves as they evaluated through safety considerations. Therefore, each pair of curves, i.e., proceeding and following, were examined and their crash rates both during the day and night were analyzed. Crashes were distributed as noted above in order to properly account for the sequence of curves along each corridor direction. This approach would allow for the determination of a minimum crash rate that could be considered as critical and above which the combination of curve radii could result in an inappropriate speed change and thus potentially lead to a crash.

This analysis was achieved utilizing the anticipated crashes obtained through the day and night IHSDM models. Crashes were distributed to the corresponding travel directions utilizing the process described above and plotted as curve combinations considering pairs of proceeding and following curve radii. Fig. 2 shows an example of this analyses where the relative number of crashes is reflected through the size of the circle. The size of the circle can be used to indicate critical curve combinations where larger circles could pose a greater safety issue as a result from the specific curve radii combinations. One can use this as guidance and define graphically the following areas:

- Good: Areas with only small circles representing safe combinations of successive curve radii. The presence of some larger circles needs further evaluation to determine other potentially confounding crash factors, i.e., speeding, low skid resistance etc.
- Acceptable: Area with a higher concentration of larger circles representing acceptable combinations and not including successive curve radii with high crash rates.
- Not Acceptable: Area where most of the large circles are present and it reflects combinations that could result in crashes denoting an unsafe design.

The Fig. 2 data indicate that there are differences between day and night. The small number of roadway segments does not allow for a quantitative approach to clearly define these areas based on all curves. This issue was partially addressed while considering curves above a critical crash rate regardless of the number of crashes (Fig. 3). Prior studies have defined a rate of 4.5 crashes per MVMT as a threshold between design consistency and safety (FHWA 1999) and this was used for the Kentucky roads. The new areas were thus defined based on the following approach:

- Good: includes 10 percent of the crashes noted.
- Acceptable: includes approximately 30 percent of the crashes including those considered in the Good area.
- Not Acceptable: include the remaining 70 percent of the crashes.

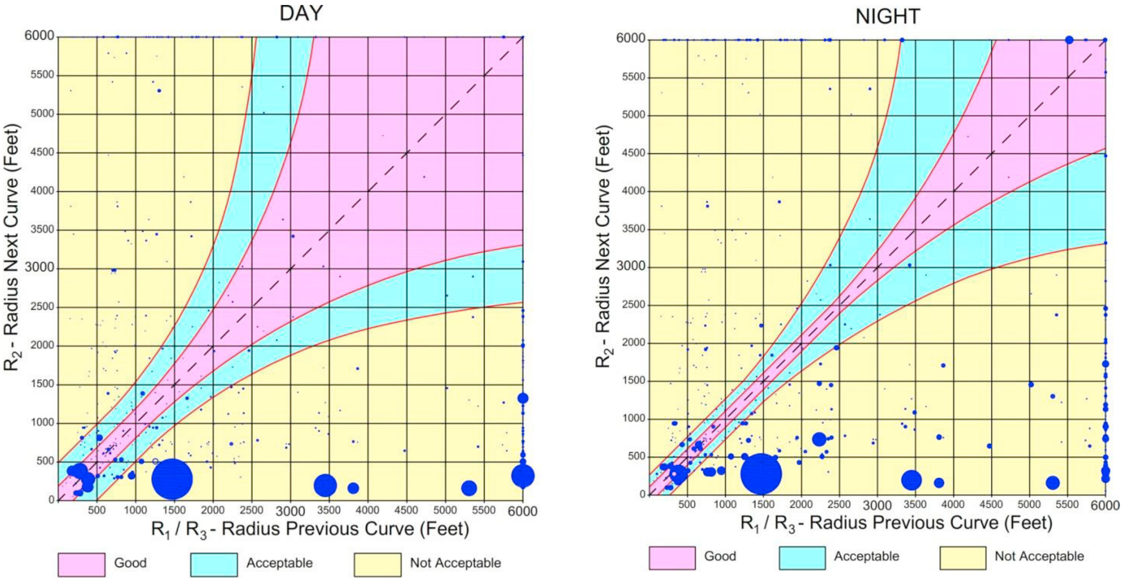

Fig. 2. Relationship between successive curves for day and night; all curves, Kentucky

One can argue that these boundary values are arbitrary, but they were set to simply evaluate, and possibly illustrate, the potential need for separate design consistency evaluations between day and night. The addition of more segments in the future will allow for a more robust approach in defining these boundaries. A different critical crash rate was used for Greece (0.9 crashes per MVMT) and for Italy (0.6 crashes per MVMT) due to the lower crash rates observed along the segments considered. Moreover, the availability of only injury and fatal crashes for the Greek and Italy data necessitated the adjustment of this value based on the ratio of (Injury + Fatal / Total) for Kentucky crashes resulting in the 0.9 crashes per MVMT. The data in Fig.3 support the need for separate design consistency evaluations between day and night in order to identify acceptable successive radii under each condition.

5. Discussion and conclusions

The objectives of this research were to examine and document the possible influence of roadway geometry and especially horizontal curvature on night crashes and determine whether additional design consistency evaluation is needed for nighttime conditions. Crash statistics in Kentucky, Greece and Italy support the fact that almost half of the crashes occur at nighttime. This problem can be exacerbated considering that typically only a third of the daytime AADT is present during the night. This study utilized a small number of roadway segments in Kentucky, Greece and Italy to address the study objectives. The data clearly support that the nighttime crash rates are higher than those observed during the day when considering the curve radius. Curves with small radii showed an increase in crashes and crash rate at night when they were compared to their corresponding daytime crashes. These crash differences were always present, even though some were small.

Several of the guidelines indicate that a ratio of the preceding to following curve, i.e., R1/R2, should not exceed 1.5 in order to allow for safety and design consistency (AASHTO 2018). The data here shows that in general this rule is in place for the day conditions but there is a need for revision for nighttime, since the acceptable range results in much lower ratios. The consistency among the three countries regarding the presence of differences between day and night relationships regarding successive curvature radii and safety also supports this need and it cannot be considered simply a coincidence but rather an indication that there is indeed an issue that merits further study.

Design consistency was defined here as the combination of radii of successive curves. Fig. 2 clearly demonstrated the differences in crash experience between day and night when considering the relation between two successive curves. The data showed that curve combinations that would perform adequately during the day could be creating

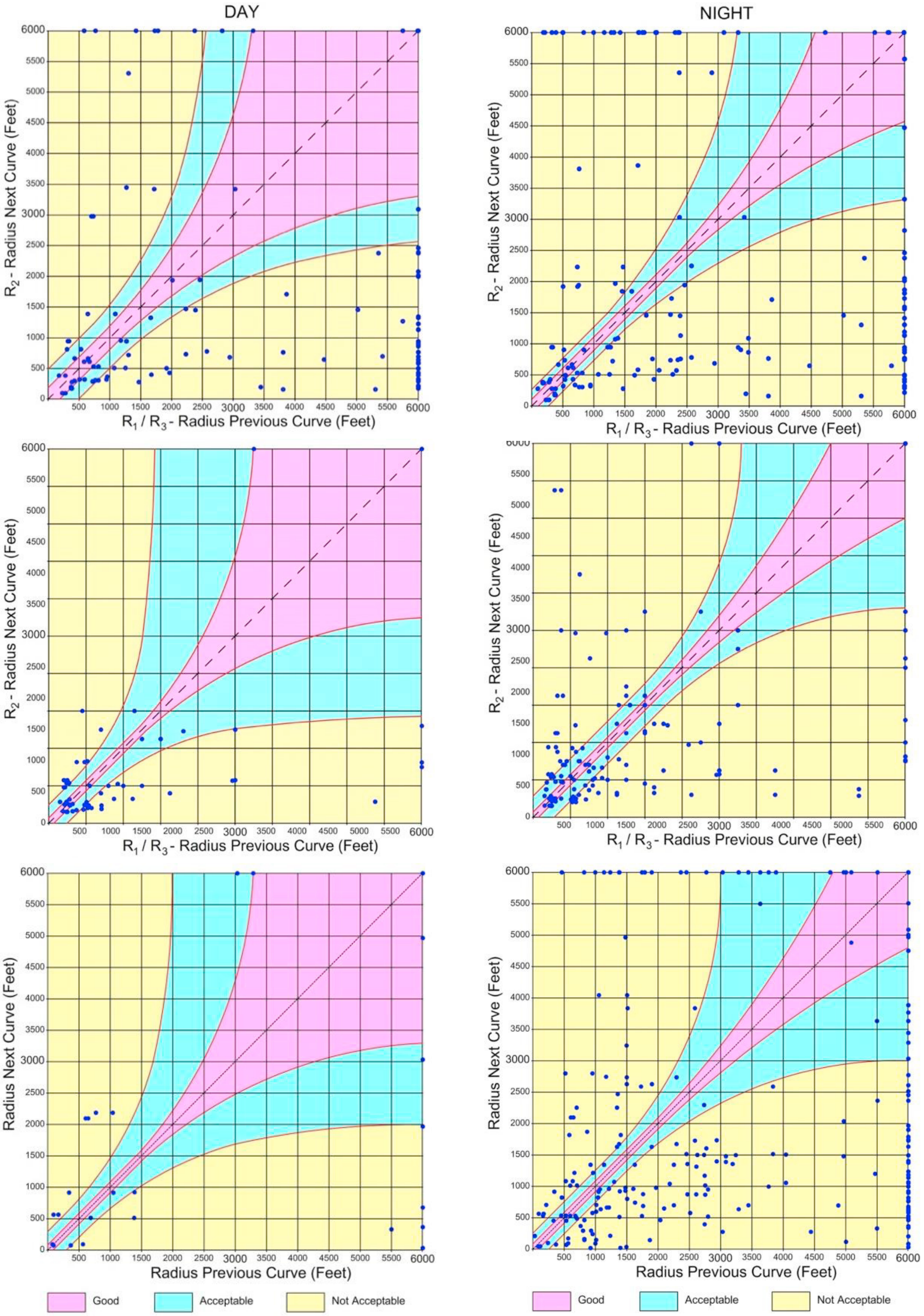

Fig. 3. Relationship between successive curves for day and night (a) Kentucky, USA curves with rates>4.5 crashes/MVMT; (b) Greece, curves with rates>0.9 crashes/MVMT; (c) Italy, curves with rates >0.6 crashes/MVMT

safety issues at nighttime supporting the notion that at night due to limited sight distances drivers do not have adequate time to adjust their speeds at nighttime while they should be able to do safely during the day. This finding supports the notion of reconsidering design consistency models for addressing nighttime conditions separately from daytime and thus improve roadway safety and partially address the nighttime crash problem.

It is clear that the analysis presented her is based on a small number of roadway segments and it is not enough to allow for a more quantitative model. Additional work is needed to further evaluate and refine the nomographs developed here through the addition of more roadway segments. Designers will develop a design for an alignment and then perform a design consistency check to determine whether the radii of successive curves are appropriate for both day and night conditions utilizing the nomograph shown in Fig. 3. If either the day or night checks result in a combination that is not at least within the acceptable range, then a new combination of radii needs to be identified and considered for the final design. It should be emphasized once more that this was an investigative research effort aiming to investigate the presence of an issue that designers may not be aware of and alert them t on the need of separate checks for design consistency for nighttime conditions. Additional data will refine the nomopgraphs shown in Fig. 3 and thus result in developing safer designs to address nighttime crashes and overall roadway safety.

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