Driver tolerance of lateral accelerations on horizontal curves

Eric D. Hildebrand and Jonathan Lewis

Abstract: There are many roadways where existing horizontal curves fail to meet minimum geometric design standards for financial or geographic reasons. Advisory speeds, typically set with a ball-bank indicator, are posted on these curves to ensure that drivers are not subjected to uncomfortable levels of lateral accelerations as they negotiate the curve. The threshold levels of lateral acceleration as estimated by ball-bank indicators vary considerably between jurisdictions with many still basing their guidelines on studies dating back to the 1930s and 1940s. This study investigated present day ball-bank indicator tolerance levels by analyzing actual driver behaviour on 30 curves posted with advisory speeds in New Brunswick. A unique method of data collection involving digital video analysis enabled the development of vehicle speed profiles approaching and throughout the curves. The results indicated that drivers tolerate higher levels of discomfort as they navigate curves than currently assumed. This finding justifies raising the ball-bank indicator threshold levels used for posting advisory speeds. Inconsistencies between actual posted advisory speeds, policy guidelines, and jurisdictional implementation have also been identified. Recommendations address both short and long-term goals of updating ball-bank indicator thresholds used for signing to levels that better represent driver behaviour. Longer-term recommendations address the development of uniform signing standards across Canada so that driver expectation will not be violated between jurisdictions.

Key words: horizontal curves, operating speeds, ball-bank indicator, advisory speed sign.

Résumé : French

Mots-clés : French .

[Traduit par la Rédaction]

Introduction

All road authorities follow designated geometric design guides, which prescribe minimum horizontal radii for roadways. Compliance to these standards ensures that drivers will not experience unacceptable levels of discomfort as they negotiate curves at a prevailing posted speed limit. Unfortunately, due to financial and geographic restrictions, many horizontal curves exist that do not meet minimum requirements, requiring drivers to slow down below prevailing speed limits. Advisory speeds on curves are posted to recommend a safer and more comfortable speed to motorists where minimum radii cannot be met. Comfortable speeds are set based on assumed tolerable lateral accelerations on drivers. These assumed tolerable forces have important implications for the posting of advisory speeds on substandard horizontal curves.

The most common method currently being used to set advisory speeds is to use a ball-bank indicator to gauge the level of lateral accelerations on drivers (Bonneson et al. 2007). The data that were used to determine the ball-bank indicator thresholds of drivers is outdated as it is based on research from the 1930s (TAC 1999). There is considerable need to investigate existing speeds on horizontal curves to get a better understanding of how changes in vehicles, driv-

Received 22 May 2009. Revision accepted 6 November 2009. Published on the NRC Research Press Web site at cjce.nrc.ca on .

E.D. Hildebrand[1] and J. Lewis. Department of Civil Engineering, University of New Brunswick, Fredericton, NB E3B 5A3, Canada.

Written discussion of this article is welcomed and will be received by the Editor until 31 July 2010.

[1]Corresponding author (e-mail: edh@unb.ca).

ers, and the road environment have possibly increased driver acceptance of larger lateral accelerations while negotiating horizontal curves.

The overall goal of this study was to accurately measure minimum vehicle speeds on horizontal curves to better understand driver tolerance of lateral accelerations. Results were used to help determine if current ball-bank indicator threshold readings are appropriate for advisory speed signing guidelines.

Background

A ball-bank indicator (sometimes referred to as a slope-meter), shown in Fig. 1, is the most popular tool used to mark advisory speeds on curves. Its popularity has arisen from its simplicity of use and construction. The ball-bank indicator consists of a small steel ball sealed within a glass tube. The glass tube represents part of a circle and the degrees of the circle are marked off on the tube (20–25 degrees is typically used as the maximum required). Zero degrees is represented with the ball-bank indicator being perfectly horizontal and subjected to no lateral forces. There is a dampening liquid in the ball-bank indicator so that the ball-bank angle can be read more easily. The ball inside the indicator rolls as a result of three combined elements acting on the indicator (inside a vehicle) as the vehicle travels around a horizontal curve: centrifugal force, super-elevation of the roadway and the vehicle body roll. The amount of body roll is not constant, but changes in proportion to the other two forces, so the ball-bank indicator is not a direct measure of a lateral acceleration on the vehicle. It is a convenient tool used by practitioners to measure the combined effect of three separate elements. The centrifugal force will increase the ball-bank reading and it will be offset somewhat by the roadway super elevation. The body roll of the vehicle will increase the ball-bank reading, but overall the body roll typically represents a small proportion of the ball-bank reading.

Joseph Barnett published the most influential early work on determining safe side friction factors (for design) in his 1936 report (Barnett 1936). At that point in time, speeds were starting to increase significantly on roadways and, consequently, there was an increasing number of collisions, which focused more attention on improving roadway design and safety. A safe and comfortable design side friction factor was determined by observing the vehicle speed on a horizontal curve where a driver first felt an uncomfortable side pitch. Speed data combined with curve geometry was collected from curve sites all over the United States. The basic curve formula was then used to determine an appropriate side friction factor to use for the design of new facilities. The resulting design criterion was 0.16 for roadway design speeds up to 60 mph (96.6 km/h).

The design side friction factors worked well for new roadways, but then the problem of how to post all of the existing horizontal curves that did not meet the new standards needed to be addressed. In 1940, Moyer and Berry's very popular article on signing highway curves with safe speed indications came to press (Moyer and Berry 1940). This article came at a time when engineers realized that they needed a simple test to appropriately and consistently mark

Fig. 1. Typical ball-bank indicator.

the many substandard horizontal curves that existed so that driver expectation would not be violated as curves were negotiated. They investigated two different methods; one involved using the basic curve formula to combine the curve geometry and an assumed side friction factor to determine an advisory speed for a curve, whereas the other method used a ball-bank indicator and assumed threshold levels at different speeds to post advisory speeds. The ball-bank indicator, due to its simplicity of use, was recommended to bring consistency across the United States for posting advisory speeds. The Iowa Engineering Experiment Station performed many test runs on closed tracks with varying speeds, degrees of curvature, and super elevation in an effort to better understand ball-bank indicator readings. The results of those tests led to the recommendation that a ball-bank reading of 14 degrees was appropriate for speeds under 20 mph (32.2 km/h), 12 degrees for speeds between 20 mph (32.2 km/h) and 35 mph (56.3 km/h), and 10 degrees for speeds above 35 mph (56.3 km/h). Although this study is almost 70 years old, the ball-bank indicator threshold levels recommended are still similar to the values many provinces and states currently use.

A more recent study undertaken by Chowdhury et al. (1991, 1998) analyzed the methods of determining how advisory speeds were posted in Maryland, Virginia, and West Virginia. Tolerable ball-bank indicator readings were determined by observing driver speeds at the midpoint of curves. Vehicle speeds (85th percentile) were collected by taking one radar reading of the vehicle on the tangent and one of the vehicle at the midpoint of the curve with a minimum of 50 vehicles being observed per site. The observed curve speeds were driven in a test vehicle to determine what the corresponding ball-bank indicator readings drivers tolerated and the values found by Chowdhury et al. were compared with ball-bank indicator standards in use at the time.

The study concluded that the prevalent methods used to set advisory speeds were very conservative and that new approaches should be investigated. The study recommended that ball-bank threshold levels of 20 degrees for speeds below 30 mph (48.3 km/h), 16 degrees for speeds between 30 (48.3 km/h) and 40 mph (64.4 km/h), and 12 degrees for speeds above 40 mph (64.4 km/h) would better reflect actual driver behaviour. A criticism of this study is the assumption that minimum vehicle speeds within the curve coincide with the geometric midpoint.

The Texas Transportation Institute has recently recom-

Table 1. Ball-bank indicator readings used by neighbouring jurisdictions.

	Corresponding maximum ball-bank indicator reading (deg)				
Curve speed (km/h)	New Brunswick	Nova Scotia[a]	Quebec	Maine	Prince Edward Island
30	16	12/10	14	12	N/A
40	15	12/10	12	12	N/A
50	14	12/10	12	10	N/A
60	13	12/10	11	10	N/A
70	12	12/10	10	10	N/A
80	12	12/10	10	10	N/A

[a]Higher value is used on secondary roads.

mended a method to use a curve speed prediction model using curve geometry and tangent approach speeds to determine an appropriate advisory speed instead of using a ball-bank indicator (Bonneson et al. 2007). Although this method provides an alternative approach for jurisdictions to determine appropriate advisory speeds that are more inline with operating speeds, it is cumbersome and impractical to determine advisory speeds if the geometric and traffic data are not already available and need to be collected separately. If the geometric data are collected without the precision required, it could also have a major effect on the uniformity of advisory speeds.

There is little consistency between North American signing guidelines other than the nearly universal application of the ball-bank indicator method. The threshold values that are recommended range from the 14–12–10 degree system based on speed in the Traffic Control Devices Handbook (ITE 2001), a constant value of 16 degrees in the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA 2007), to no explicitly recommended threshold values in the Canadian Manual of Uniform Traffic Control Devices (MUTCD-C) (TAC 1998). The most recent edition of the Institution of Transportation Engineers (ITE) Traffic Engineering Handbook (ITE 2009) suggests criteria that are considerably more aggressive at 16–14–12 degrees for speed thresholds of 20 (32.2), 25 (40.2) and 30 (48.3) mph (km/h), respectively.

A regional survey was completed as part of this study to determine what ball-bank threshold levels are used in New Brunswick (NBDOT 1996) and the surrounding region (Lewis 2009) including: Nova Scotia, Prince Edward Island, Quebec, and Maine. All of the jurisdictions surveyed with the exception of Prince Edward Island, use a ball-bank indicator to determine appropriate curve advisory speeds. Advisory speed postings are set subjectively at the discretion of field foremen in Prince Edward Island.

The data in Table 1 represent the different bank–bank indicator readings that the surveyed jurisdictions use at different curve speeds. This lack of consistency across jurisdictions may lead to a violation of driver expectations for the out-of-province driver.

Study methodology

Speed data collection took place during dry, daylight conditions between May and August of 2008 and large commercial trucks were excluded from the analysis. The reason behind not including wet pavement or night time conditions was so that driver tolerance could be isolated as the probable factor affecting driver speed choice. In total, 30 sites were surveyed, all within a 100 km radius of Fredericton, New Brunswick. The posted advisory speeds at each site surveyed varied from 30 km/h to 70 km/h and local, collector, and arterial roadways were all included in this study. All sites were chosen to ensure minimal frequencies of unfamiliar drivers who might inadvertently travel the curve at an uncomfortable rate. The actual amount of survey time required at each site varied significantly due to the differences in traffic volumes on the roadways. Typical sample sizes achieved at each site ranged from 50 to 100 vehicles to ensure statistically representative results.

Drivers travelling around horizontal curves experience lateral accelerations, which increase with increasing speed. It is assumed that drivers will want to drive as fast as they comfortably can on horizontal curves and do not want to decrease their speed from the tangent approach unless their current speed on the curve makes them feel uncomfortable. Typically, individual drivers will have a tangent speed and then slow down for a sharp horizontal curve to a point where they are not uncomfortable. Following a speed reduction, the driver then continues through the rest of the curve, accelerating as they transition to the downstream tangent. Using this premise of driver behaviour, it is clear that the minimum speed that drivers reach on curves represents a speed that they comfortably tolerate. A vehicle speed profile including a tangent approach speed and three intermediate speeds around the curve was developed for each vehicle surveyed and is explained below. The minimum of the three vehicle speeds measured on the curve represents a designated tolerable speed for each individual driver and was selected for further use in subsequent analyses. Different drivers may slow down to minimums at different points on the curve, some before the midway point, some after, so this procedure of determining three intermediate speeds was felt to more accurately determine the minimum tolerable speed than other studies that simply took a single vehicle speed at the midpoint of a curve.

Radar, pneumatic tubing, magnetic traffic analyzers, and video were all considered for use for determining vehicle speeds around the study curves. Radar was selected to obtain a tangent approach speed for each vehicle; however, it was not used to determine curve speeds due to the inaccuracy of the method with the increased cosine effect on curves. Pneumatic tubing and magnetic traffic analyzers were ruled out at the onset due to the intrusiveness of those types of data collectors spaced closely together. Due to the accuracy of video and the ability to use it inconspicuously to determine vehicle speeds, it was developed as a means to determine curve speeds. Four benchmarks were located on the curve under study spaced so that the midpoint between benchmarks represented approximately the 1/4, 1/2, and 3/4 mark through the curve (utility poles, sign posts, survey stakes, etc.). Vehicles would be videotaped navigating the curve and passing each benchmark. Figure 2 shows a typical site layout. At the conclusion of the collection of video for all vehicles studied at the given curve, the distances along the lane centerline between benchmarks were measured using a measuring wheel. The video was taken to a media lab at the University of New Brunswick where it was analysed on a frame-by-frame basis. The number of frames between benchmarks was counted so that the time it took each vehicle to travel between benchmarks was known (each frame represented 1/30th of a second). The distance measured was divided by the time calculated to develop three vehicle speeds for the curve corresponding to the space mean speeds between each of the four benchmarks. The space mean speeds between benchmarks approximated spot speeds at the midpoint between benchmarks as the change in vehicle speeds between benchmarks was small. The three curve speeds were combined with the radar tangent approach speed to complete a speed profile for each vehicle. The minimum speed from the three vehicle curve speeds was chosen as the driver-selected tolerable speed for the analysis portion of this study.

The error associated with this approach was dependent on the camera's frame speed (30 per second), vehicle operating speed, and distance between successive benchmarks. A combination of high operating speeds and closely spaced benchmarks would yield higher errors. The maximum error that would be experienced would occur when there was exactly a 1/2 frame error in time at each benchmark (rounded to the nearest frame number) or 1 frame (1/30th of a second) total error for a speed measurement between benchmarks. The combination of the maximum one frame error in time measurement with the benchmark spacing and vehicle speeds observed at each site resulted in an error in speed measurement of no more than 2% for an individual vehicle on one portion of the curve for all sites chosen for this study.

The ball-bank readings that correspond with the observed mean and 85th percentile minimum curve speeds were determined by outfitting two exemplary passenger vehicles with ball-bank indicators following video analyses. Each curve was driven several times until a consistent ball-bank reading was obtained at the posted advisory speed as well as the measured mean and 85th percentile curve speeds. The ball-bank indicator was calibrated to zero degrees on a flat surface before any test runs. Care was taken to drive at a constant speed in the middle of the travel lane for each test. The tire air pressure was also taken prior to any testing.

Study results

The data in Fig. 3 graphically show the observed mean and 85th percentile curve speeds corresponding to the posted advisory speed at all 30 sites. The number of sites (n) corresponding to each speed zone is noted in the figure. It was found that both mean and 85th percentile speeds were well above the posted advisory speeds at the sites studied. These

Fig. 2. Typical site set-up.

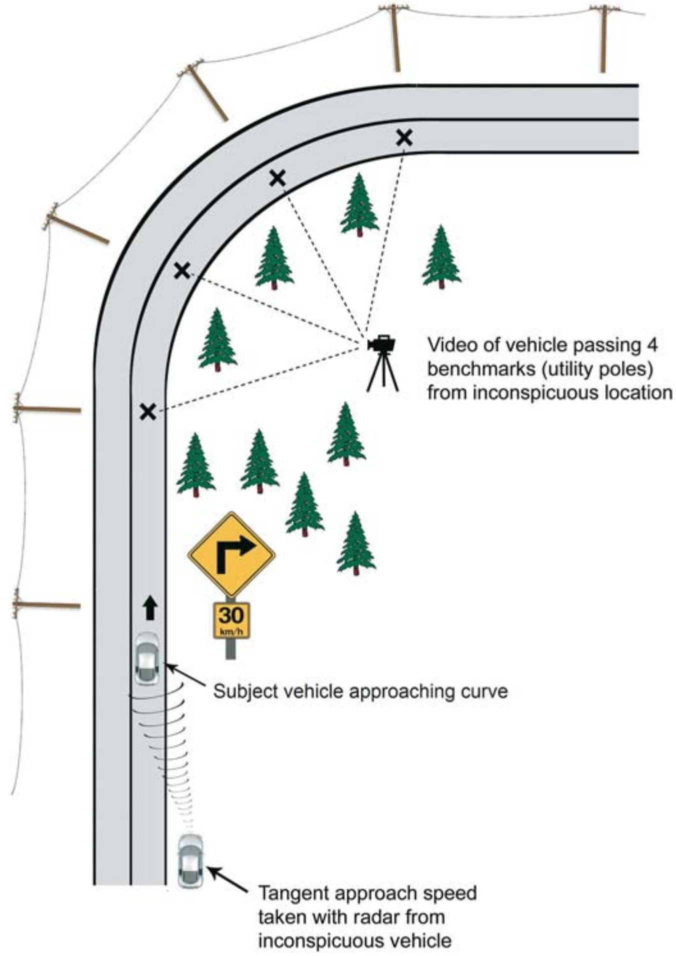
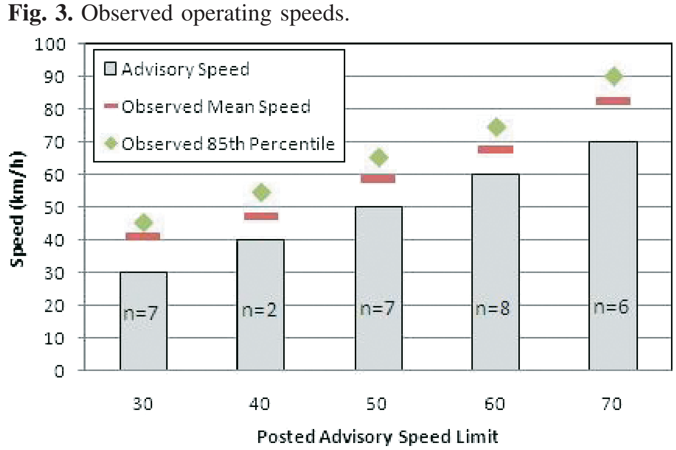


Fig. 3. Observed operating speeds.



data indicate that drivers generally are tolerant of higher lateral accelerations associated with higher operating speeds through curves. In other words, the criteria used to post advisory speeds appear to be unnecessarily conservative.

The same data are summarized in Table 2 and include measures for all study sites combined. It is noted that the average mean speed was found to be 9.4 km/h above the posted advisory, whereas the average 85th percentile speed was 15.9 km/h above the posted advisory. This is consistent with research reported in the recent edition of the Traffic

Table 2. Observed operating speeds compared with posted advisory speeds.

Posted advisory speed	Average observed mean speed (km/h above posted)	Average observed 85th percentile speed (km/h above posted)
30	10.9	15.2
40	7.3	14.5
50	8.6	15.2
60	7.8	14.5
70	12.5	20.1
All zones combined	**9.4**	**15.9**

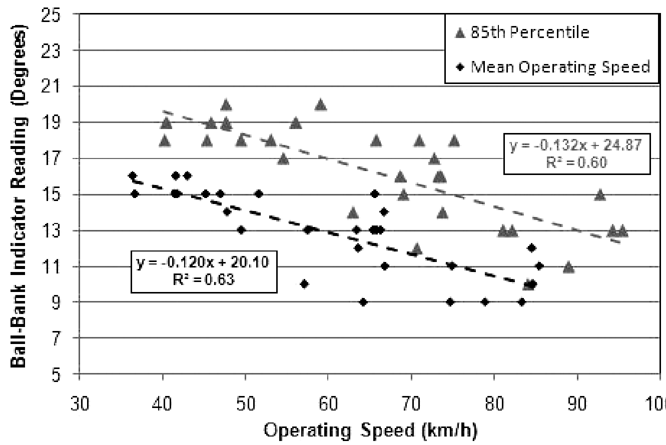
Engineering Handbook (ITE 2009) where it was concluded that drivers typically exceed advisory speeds by 8 to 10 mph (13 to 16 km/h).

A driver was considered compliant with an advisory speed if their minimum operating speed from the video analysis was found to be at or below the posted advisory speed. Compliance rates for speed levels ranged from 1.3% for the 30km/h posted sites to 20.7% for the 50km/h posted sites. Overall the compliance rate was considered rather low at only about 10%. Such a low rate was a surprising finding considering the adoption of less-conservative (higher ball-bank threshold levels) standards in New Brunswick than in neighbouring jurisdictions. Part of the reason for the low compliance rate may be due to a lack of consistency in following guidelines for posting advisory speeds within the province. All of the sites were analyzed to see what the advisory speeds should be posted according to New Brunswick's written procedures. It was found that only 14 out of 30 sites were posted correctly. All 16 sites posted that were inconsistent with the written procedures had posted advisory speeds that were lower than what the written procedures dictated. This lack of consistent posting requires further investigation with future studies.

A paired student *t* test between the means of the tangent approach speeds and the curve minimum speeds showed that 29 out of the 30 sites observed had a statistically significant drop in speed from the tangent to the curve so those 29 sites were included in subsequent analyses. It was assumed that as the driver slowed down, their minimum speed within the curve represents a tolerable speed with a corresponding ball-bank indicator reading. Figure 4 shows the plot of the ball-bank indicator readings that correspond to the mean and 85th percentile minimum curve speeds. A simple linear regression using sum of least squares was used to fit a trend line to the data. There is a fair degree of scatter in the data as is evident from the moderate R-squared values.

There are several factors that would have contributed to the scatter in the data. Individual drivers have different tolerances to lateral forces as they travel around horizontal curves so this range of tolerances is probably at least partially responsible for the scatter in the data. Roadways cannot be designed or signed to individual driver behaviour, but traditionally are designed or signed for a conservative (or sometimes 85th percentile) driver tolerance. There are other factors that might also have affected the ball-bank tolerances including: the signage at the site, the sight distance around the curve, the presence of edge lines, time of day, range of vehicle types, and the physical characteristics of the site.

Fig. 4. Ball-bank indicator readings corresponding to operating speeds.



Although it would have been possible to include some of the above factors in the regression analysis, which possibly might have improved the model fit, it is not practical to include any of those factors in a field determination of an appropriate advisory speed. The ball-bank threshold level is a well understood, well accepted method of determining advisory speeds and introducing additional variables for consideration would likely not be well received by practitioners.

The data in Fig. 5 compare the ball-bank indicator tolerance levels for the mean and 85th percentile speeds from New Brunswick to two other studies that were documented in the literature review. The study from Chowdhury et al. (1991) resulted in a higher initial ball-bank indicator level, but decreased at a greater rate compared with the New Brunswick observations. The data were only available for the 85th percentile speed for the Chowdhury study for this comparison. The results from the 1940 study (Moyer and Berry 1940) were also included in Fig. 5 because the values that were recommended are still commonly used by many jurisdictions. A key NCHRP study (Lyles and Taylor 2006) found that the most common ball-bank threshold levels used in the United States are still 10 degrees for high speeds and 12 degrees for lower speeds (using a 14 degree threshold was less common) as recommended by the 1940s report. This study's survey of regional jurisdictions also found that the 14–12–10 threshold levels were still commonly employed. Figure 5 clearly shows that the 14–12–10 threshold levels that were recommended by Moyer and Berry and still used by some jurisdictions are well below the ball-bank levels that correspond with both the observed mean and 85th percentile speeds. It is expected that jurisdictions that use those threshold levels (14–12–10 or 12–10) would have very low compliance rates with advisory speeds especially at low speeds and are not consistent with what drivers currently consider to be comfortable operating speeds.

The data in Fig. 6 compare the ball-bank indicator tolerance levels for the observed mean and 85th percentile minimum curve speeds from this study's observations to the current written policy signage guidelines in New Brunswick as well as the recommended practice outlined in the US edition of the MUTCD (FHWA 2007). The ball-bank threshold levels recommended in the New Brunswick sign manual (NBDOT 1996) actually match very closely with the current

Fig. 5. Comparison of ball-bank indicator studies. NB, New Brunswick.

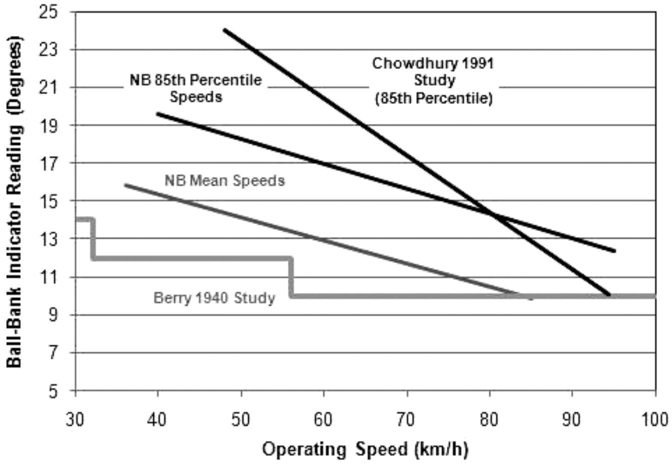
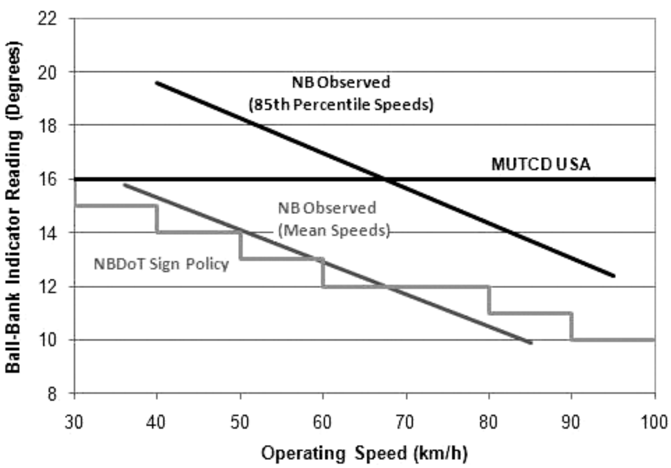


Fig. 6. Comparison of ball-bank indicator comfort limits used by jurisdiction. NB, New Brunswick; NBDOT, New Brunswick Department of Transport; MUTCD USA, Manual on Uniform Traffic Control Devices USA.



ball-bank indicator threshold levels corresponding to the mean operating speeds. This is surprising due to the very low compliance rate in New Brunswick with respect to advisory speeds (about 10%), which may be explained by the many posting inconsistencies noted previously. It is clear that the MUTCD's recommendation of using one constant value for a threshold value in the United States (FHWA 2007) does not match driver behaviour in New Brunswick. This is particularly problematic at higher speeds where the discrepancy increases resulting in higher posted advisory speeds that could violate driver expectations.

Conclusions

The use of digital video to monitor vehicles as they travel through horizontal curves resulted in the ability to generate individual speed profiles with only minimal errors. This method can provide an unobtrusive and inconspicuous means to study driver speed adaptation.

The observed minimum speeds that drivers select while negotiating horizontal curves were found to be well above

Table 3. Recommended ball-bank indicator threshold levels.

Curve speed (km/h)	Short-term recommended maximum ball-bank reading (deg)	Long-term recommended[a] maximum ball-bank reading (deg)
30	16	19
40	15	18
50	14	17
60	13	16
70	12	15
80	10	14
90	10	13
100	10	12

[a]Assuming uniform implementation nationally.

posted advisory speeds. The average mean and 85th percentile minimum curve speeds were found to be 9.4 and 15.9 km/h above the posted advisory, respectively. This suggests that current criteria used to post advisory speeds appear to be unnecessarily conservative. Consequently, driver compliance rates to posted advisories were found to be only about 10%.

Less than half of the sites studied had advisory speed limits that were posted in accordance with current provincial practice. A lack of uniformity can result in a violation of driver expectations leading to a reduction in safety levels.

Recommendations

In the short term it is recommended that jurisdictions follow the tolerable ball-bank levels found in this study representing the mean curve speed. Although the 85th percentile speed may be a more appropriate level, it is recommended to use the mean levels for the time being as this would represent only a small change to the current standards and the consequences of a driver expecting signing based on older more conservative ball-bank levels would be minor. Adoption of thresholds based on 85th percentile speeds would result in much more aggressive posted advisory speeds. This approach should only be followed if it could be implemented uniformly among jurisdictions.

The data summarized in Table 3 show the recommended ball-bank indicator readings corresponding to the test curve speed. Extrapolation was used for the recommended ball-bank readings corresponding to the 30, 90, and 100 km/h curve speeds because they were outside of the actual mean speed data collected for this study. Note that it would be rare that advisory speeds would be posted at 90 km/h or 100 km/h because prevailing posted speeds are typically at least 20 km/h higher. Highways posted at 110 km/h or 120 km/h have relatively few substandard designed curves.

The short term recommendations for speeds above 80 km/h were held constant at a ball-bank level of 10 degrees to match what many jurisdictions currently use. The values recommended for longer term implementation are more in line with the latest values recommended by ITE (2009).

Another important aspect about posting advisory speeds is the maximum differential required between the posted and (or) operating speed on the tangent approach to a curve and the comfortable curve speed required to warrant an advisory speed sign being posted. The literature review and jurisdiction survey in this study found that there is a lot of variability in this differential value between jurisdictions ranging from 0 to 20 km/h It is recommended that an advisory speed sign be posted whenever the comfortable curve speed determined from the maximum ball-bank readings in Table 3 is equal to or less than the tangent posted regulatory speed limit. If the actual vehicle operating speeds are known on the tangent then this can be substituted for the tangent posted speed. It is expected that most jurisdictions do not collect the tangent approach speeds when setting advisory speeds, so most jurisdictions likely currently use the posted tangent speed to compare with the comfortable curve speed. This recommendation is stricter than some jurisdictions currently use, but this study has found that some actual tangent operating speeds can be much greater than the actual tangent posted speed limit, so it is important to reiterate to the driver that they should slow down (even if it is just to the existing posted speed limit) for an upcoming curve so that they will not feel uncomfortable.

There needs to be a national effort to set uniform standards or guidelines so that there is a consistent application of advisory speeds across the country. A survey found that New Brunswick and all three of its neighbouring provinces have different procedures on how and when to post advisory speeds and what ball-bank indicator thresholds to use. Advisory speeds provide very important safety information to drivers who are unfamiliar with the area so an inconsistent application can lead to driver expectations being violated. The Transportation Association of Canada is the logical agency to spearhead such an effort as they publish the MUTCD-C. It is recommended that similar driver tolerance studies to this one completed in New Brunswick be undertaken in other areas of Canada to ensure that any new recommended national guidelines better reflect actual driver behaviour. Furthermore, results from this study suggest that signing compliance to existing ball-bank thresholds can be very poor in the field. Improved diligence by road authorities may be necessary to ensure consistent application of advisory postings.

Although this was an extensive study of actual driver behaviour on horizontal curves, there are still questions that have been left unanswered that future research should address. This study focused on dry daylight conditions only so future research could include how pavement conditions (wet versus dry) and light conditions affect driver behaviour on curves.

Acknowledgements

The authors acknowledge the financial assistance provided by the Natural Sciences and Engineering Research Council of Canada in support of this research.

References

Barnett, J. 1936. Safe side friction factors and super-elevation design. Highway Research Board Proceeding of 16th Annual Meeting, Washington, D.C.

Bonneson, J., Pratt, M., Miles, J., and Carlson, P. 2007. Development of guidelines for establishing effective curve advisory speeds. Texas Transportation Institute Technical Report 0–5439–1, College Station, Texas.

Chowdhury, M., Warren, D., and Bissell, H. 1991. Analysis of advisory speed setting criteria. Public Roads, **55**: 65–71.

Chowdhury, M., Warren, D., Bissell,H.and Taori, S. 1998. Are the criteria for setting advisory speeds on curves still relevant? Institute of Transportation Engineers Journal, **68**(7): 32–45.

Federal Highway Administration (FHWA). 2007. Manual on uniform traffic control devices. 2003 Edition with Revisions Number 1 and 2 Incorporated. Washington, DC.

Institute of Transportation Engineers (ITE). 2001. Traffic control devices handbook. Washington, D.C.

Institute of Transportation Engineers (ITE). 2009. Traffic engineering handbook. Washington, DC.

Lewis, J.B. 2009. Analysis of driver speeds and comfort on horizontal curves in New Brunswick, Master's Thesis, University of New Brunswick, Fredericton, N.B., Canada.

Lyles, R., and Taylor, W. 2006. Communicating changes in horizontal alignment. National Cooperative Highway Research Program Report Number 559. Washington, D.C.

Moyer, R., and Berry, D. 1940. Marking highway curves with safe speed indications. Highway Research Board Proceeding of 20th Annual Meeting, Washington, D.C.

New Brunswick Department of Transportation (NBDOT). 1996. NBDOT sign manual. Fredericton, N.B.

Nova Scotia Department of Transportation (NSDOT). NSDOT regional traffic supervisor field manual. Halifax, Nova Scotia.

Transportation Association of Canada (TAC). 1998. Manual of uniform traffic control devices for Canada. Ottawa, Ont.

Transportation Association of Canada (TAC). 1999. Geometric design guide for Canadian Roads. Ottawa, Ont.